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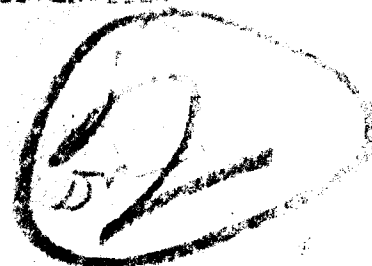
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08733

DEVELOPMENT OF A MATHEMATICAL PERFORMANCE
PREDICTION MODEL FOR
ROTARY-HYDRAULIC-TYPE ARRESTING GEARS

Phase Report
23 March 1972

by

George M. Leask
Computer Division

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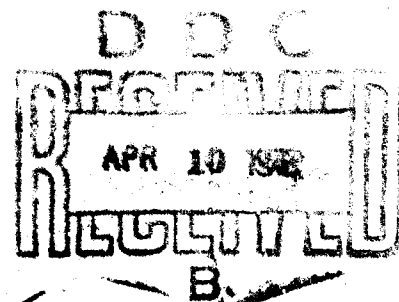PREDICTION MODEL FOR
ROTARY-HYDRAULIC-TYPE ARRESTING GEARS

Phase Report
23 March 1972

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ABSTRACT

This mathematical model is designed to provide predicted dynamic performance data of shorebased rotary-hydraulic-type aircraft arresting gears. A Navy Model E-28 arresting gear is used for specific comparison between predicted results of the computer solution and actual test results. The simulation of an arrestment of a vehicle under a particular set of conditions is accomplished by putting information (data) into the computer. The input data specifies values for the installation geometry and mechanical properties of the arresting system and the test vehicle. Predicted dynamic values of forces and motions of the test vehicle, purchase system, and tape reel are printed out versus time at a predetermined incremental time.

This report is a phase report on the development of the model and contains the early analytical design approaches, the most current analytical approach with the computer program, and instructions for execution of the computer program.

## ACKNOWLEDGEMENTS

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Mr. William Sangtinette

Mr. Norman O'Rorke

Mr. Patrick Stevens

Mr. Wayne Knapp

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I  INTRODUCTION

A.  The E-28 Mathematical Model was designed and is being developed by the Computer Division, Engineering Department, NATF, to simulate the performance characteristics of the E-28 arresting gear and any similar shorebased rotary-hydraulic arresting gear, such as the BAK-13 or 44B-2D.

B.  The ultimate objectives of the design are:

1.  To perform parameter predictions which aid in arresting-gear component design, equipment modification, and the determination of gear performance changes due to various proposed and/or actual installation configurations.

2.  To reduce the test time of a calibration test program by generating performance data which could act as "fill in" data once the upper and lower limits of the engaging-speed and vehicle gross-weight spectrums have been established through actual arrestments, provided good agreement exists.

C.  This report has been prepared to document the model in its current state of development and to discuss the additional capability necessary to achieve the above objectives (paragraphs B1 and B2).

## II  DESCRIPTION OF THE E-28 ROTARY-HYDRAULIC-TYPE ARRESTING GEAR

A.  **Purpose:**  The Navy E-28 arresting gear is a shorebased emergency arresting gear designed to arrest all U.S. Navy arresting-hook-equipped airplanes under conditions of aborted takeoff or landing overrun.

B.  **Capabilities:**  An airplane engaging the arresting gear will be stopped within a runout distance of approximately 1,000 feet.  The maximum energy absorbing capacity of the gear is 76 million foot-pounds (nominal).  Engagements can be made from either runway direction and at points up to 40 feet on either side of the runway centerline.

C.  **General Description of the Arresting-Gear Operation:**  As shown in Figure 1, two identical energy absorber units and runway-edge sheaves are located on opposite sides of the runway and are connected, through nylon purchase tapes, to a steel wire-rope deck pendant.  Arrestment of a landing aircraft is accomplished by engagement of the aircraft arresting hook with a pendant stretched across the runway.  The attached purchase tapes are pulled off the six-foot-diameter drum on each arresting gear.  Each drum is splined to a shaft which turns a vaned rotor between vaned stators in a housing filled with a water/glycol mixture.  The turbulent fluid resistance caused by the stator and rotor interaction (water brake) decreases the rotational speed of the drums, thereby slowing down the purchase-tape payout which in turn applies a braking force on the aircraft.  The ensuing  fluid turbulence converts the landing aircraft's kinetic energy into heat.  A cooling system is provided to dissipate this heat during rapid-cycle operations.  After the aircraft has been safely brought to a stop, and the arresting hook disengaged, the pendant and nylon tapes are returned to battery position by an air-cooled gasoline engine driven retraction system.

## III  BACKGROUND OF MODEL DEVELOPMENT

A.  <u>General</u>:  The development of the model from the initial working
model to the current model has mainly involved modifications of the pen-
dant/tape geometric configuration that occurs during an arrestment and is
used as the basis for parameter generation.

B.  <u>Design Progress to Date</u>

1.  <u>Initial Design</u>:  The initial E-28 mathematical model produced
dynamics of the gear directly from the motion of the arresting aircraft.
The geometry of the pendant/tape pattern was assumed to be triangular in
shape.  The pendant/tape was assumed to be in a straight line proceeding
from the arresting hook to the runway-edge sheaves throughout the entire
arrestment.  The early results of model runs indicated that a more sophis-
ticated approach was necessary.

2.  <u>Interim Design</u>

a.  The kink wave is a triangle-shaped deformation of the run-
way pendant that is generated from the impact of the arresting hook and
represents the motion of stress propagation in the pendant/tape setup.

b.  The idea of designing kink-wave phenomenon into the math
model originated after studying reports written by F.O. Ringleb (refer-
ences (a) and (b)) concerning cable dynamics.  The addition of kink-wave
motion to the program design was necessary to more accurately predict
E-28 arresting-gear performance, especially arresting-hook-load and tape-
tension values, for the initial part of an arrestment.  The introduction
of kink-wave geometry into the model forced the dynamics of the arresting
system to be generated with respect to the motion of the kink-wave.  The
various methods that were devised to simulate actual kink-wave paths
which hold for the entire simulation of an arrestment are:

(1)  arresting-hook-point-to-sheave motion

(2)  arresting-hook-point-to-sheave/sheave-to-arresting-
hook-point motion

(3)  arresting-hook-point-to-sheave/sheave-to-arresting-
hook-point/arresting-hook-point-to-sheave motion

3.  <u>Most Recent Design</u>:  The best results that have been obtained
to date are from the current model.  This approach assumes that the kink
wave travels from arresting-hook point to sheave repeatedly.  That is, when
the program determines that the kink wave has reached the runway-edge sheave
and is ready to "bounce back" toward the hook, program logic forces a new
kink wave to emanate from the hook and progress toward the sheave.  Although
not in agreement with the classical kink-wave motion described by Ringleb in

reference (a), this method has proven to give the most accurate prediction results to date. The results of this method are compared to the results of earlier design approaches in the form of a composite plot of arresting-hook load versus time in Figure 2.

## IV  ACTUAL ARRESTMENT DESCRIPTION

A.  The purpose of the arresting system is to dissipate the engaging kinetic energy of an aircraft.  This is accomplished by transmitting the vehicle's energy through the purchase tapes into the tape-reel absorber units where the energy is converted into heat by the action of fluid turbulence.  During the course of an arrestment there are, therefore, three main types of motion caused by the action and reaction of the system components:

    1.  Tape-reel and rotor motion

    2.  Pendant/tape (kink-wave) motion

    3.  Vehicle motion

The force interaction between these three types of motion is the principal basis for the mathematical model simulation of an arrestment.

B.  The following is an account of how each type of motion changes as the arrestment proceeds:

    1.  **Before Impact**

        a.  Arresting Gear - motionless

        b.  Pendant/Tape - motionless

        c.  Vehicle - approaching pendant at a predetermined speed and weight

    2.  **At Impact**

        a.  Arresting Gear - motionless

        b.  Pendant/Tape - set in motion by action of kink-wave generated upon impact

        c.  Vehicle - speed at impact is the engaging speed for the arrestment

    3.  **After Impact (period of arrestment)**:  The initial braking force on the vehicle is slight and is imposed by tensions due to purchase-tape elongation.  Once the tape reels are in motion, however, the main retarding (braking) force is due to the hydraulic brake connected to the tape reel.  A typical arrestment, therefore, will be described in two sections:  the first called the dynamic region where there is only slight retardation of the vehicle due to kink-wave motion causing purchase-tape elongation; and the second called the hydraulic region, where the main retarding forces on the vehicle are encountered.

a. **Dynamic Region**

(1) Arresting Gear - tape reels start to rotate due to tension instilled by kink waves. Fluid pressure in absorber is still not affected.

(2) Pendant/Tape - kink wave is reflected off of runway-edge sheaves and travels back and forth repeatedly from arresting-hook point to sheave, causing the kink-wave "humps" in the recorded tape-tension values.

(3) Vehicle - speed starting to feel effects of tension pull of tapes.

b. **Hydraulic Region**

(1) Arresting Gear - tape reels are increasing speed rapidly because they are feeling directly the pull of the vehicle's weight. Fluid pressure in absorber unit increases steadily.

(2) Pendant/Tape - kink waves have more or less damped out although effects on tape tension are still noticeable. Tape tensions are due almost entirely to the retarding force the tape reel fluid has on the vehicle via the purchase tape.

4. **End of Arrestment:** When all of the vehicle's kinetic energy has been transformed into heat in the absorber units through the action of fluid turbulence, the vehicle comes to a stop and the arrestment is complete. Reel acceleration, arresting-hook load, absorber pressure, and tape tensions reached their maximum values in the hydraulic region of the arrestment and then decreased to their initial pre-impact values[1].

---

[1]This is generally true although sometimes the maximum values of arresting-hook load and tape tensions can reach their peaks in the dynamic region for certain arrestment runway configurations. Also, due to tape stretch there may be a load in the system when the vehicle is stopped accounting for small arresting-hook-load and tape-tension values.

## V  SIMULATED ARRESTMENT DESCRIPTION

A.  General:  The computer program developed is a finite incremental
analysis of arresting-gear dynamics.  The simulation of a test event
(aircraft arrestment) is accomplished by relating mathematically the
interreactions between vehicle, kink-wave, and tape-reel motions.  Param-
eter computation sections of kink-wave velocity, tape tension and elon-
gation, tape-reel acceleration, etc., which have been developed in
separate studies are applied collectively, while conforming to the pre-
determined shape or pattern of kink-wave design, to obtain performance
results.

B.  Calculation Section Logic

1.  The calculation section logic consists of equation segments
which compute specific physical properties of the arrestment such as
forces, torques, motions, and distances.  Each segment was developed
independently and then combined to provide for the calculation of the
key motion generation parameters--vehicle and reel accelerations.

2.  The logic that begins the calculation loop and generates
simulated motion contains equations which are actually simple integration
techniques.  Values of accelerations (tape reel and vehicle) are provided
from the previous pass through the calculation loop.  The integration
technique is applied which results in values of velocity and speed (tape
reel and vehicle), and the procedure is repeated to obtain values for
tape-reel revolution and vehicle runout.  The basic loop logic is
diagrammed below:

```
                                                          ←─────VEHICLE ACCEL
 ┌──────────────────────────────────────────────────────────────────┐
 │          VEHICLE    VEHICLE                                  ↑     │
 │ START    ACCEL      RUNOUT                                   │     │
 │ OF                          TAPE ON   TAPE    TAPE    ARRESTING    │
 │ CALC                        DECK      ELONG   TENSION  HOOK LOAD   │
 │ LOOP     TAPE-REEL  REEL                                           │
 │          ACCEL      ROTATION                           ↓           │
 └──────────────────────────────────────────────────────────────────┘
                                              ←─────REEL ACCEL
```
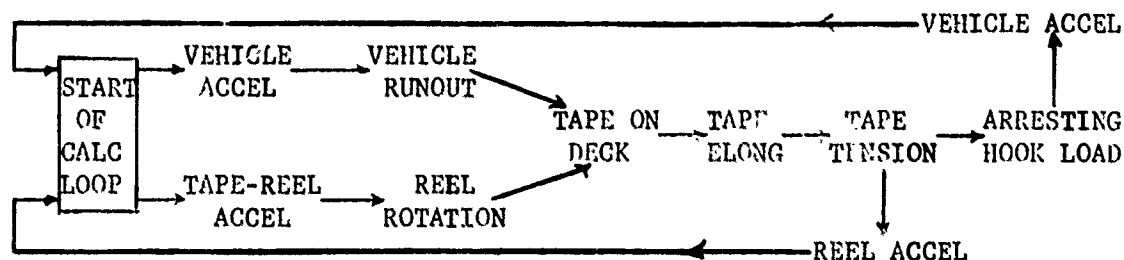
3. An explanation illustrating how vehicle speed is obtained from vehicle acceleration follows:

letting  $V_2$ = vehicle speed at end of time increment (VELNS2),

$V_1$ = vehicle speed at start of time increment (VELNST),

$A_2$ = vehicle acceleration at end of previous time increment, (VACC2),

$A_1$ = vehicle acceleration at start of previous time increment (VACC),

T = time,

and  $\Delta t = \dfrac{\Delta T}{2}$.

Instantaneous speed can be approximated by a value of average speed or

$$V_2 = V_1 + \Delta t \, (A_1 + A_2).$$

This expression represents an integrated process which utilizes the average of two accelerations, $A_1$ and $A_2$, within a specified time increment, $\Delta T$, to obtain an average speed difference, $\Delta V = \Delta t \, (A_1 + A_2)$.

4. Ideally, the most accurate simulation can be obtained when $\Delta T$ approaches zero, then $\Delta V = dV$. This program assumes that sufficient accuracy is obtained by letting the time increment $\Delta t = .001$ second.

5. Passing through the calculation loop is then a matter of jumping from one logic segment to the next. The calculation loop contains seven main logic segments which compute values for:

    a. Reel and vehicle motion

    b. Pendant or tape kink-wave velocity

    c. Kink-wave coordinates

    d. Pendant/tape tensions and elongations

    e. Tape-reel inertia and acceleration

    f. Arresting-hook load

    g. Vehicle acceleration

A detailed description of how each of these segments is designed can be found in Section VI.

## VI  PROGRAM DESCRIPTION

A.  <u>General</u>:  The program description format parallels that of the program listing (Appendix A).  The description is divided according to the principal sections of program logic.  Variable titles used here are identical to those in the program.  A complete list of variable names and definitions is presented in Appendix B.

B.  <u>Computer Information</u>

1.  The program is self-contained and therefore, does not refer to external sources for information.  The program language is FORTRAN IV, and the program has been run primarily on the CDC 6600 computer, however, it can also be run on an IBM 360/65 computer.  The following is run information for an average run on the CDC 6600:

Compilation time        -  6 seconds

Run time                -  16 to 20 seconds (with .001 second
                           calculation time)

Memory locations used   -  10,000 words (60 bits per word)

Output line limit       -  2,500 lines

2.  Data is written on temporary disc storage to minimize running time.  Normally, a run is made on priority 6 status which costs 33 cents per system second.  If turnaround time is not a critical factor, the cost may be reduced by running on priority 0 at 20 cents per system second.

C.  <u>Program Sections</u>

1.  <u>Input Section</u>

a.  This section contains a dimension statement which defines the linear array, DATUM(32), which is used for program output generation and storage.  Every parameter value of output data is allocated a space in this array during calculations.  Data values can be recorded on tape or disc storage each time the calculation loop is completed or values can be recorded at a chosen time interval.  Presently the recording time interval used is .01 second.

b.  The variable JGEOR is initialized to zero.  JGEOR is a sequential run indicator and controls the number of program runs performed.

c. Read and format statements of input data complete this section and are separated to distinguish arresting-gear configuration data from event information data. The various input values that are read into the program are listed in Figure 3, which is a sample print-out of all input values.

## 2. Initialization Section

a. Initial values, that is values of variables that are required for the first pass of the main calculation loop, generally fall into three main catagories:

(1) Deck geometry

(2) Mechancial properties of arresting gear (reel, tape, pendant)

(3) Vehicle and arresting-hook properties

b. The following initialization operations are performed on variables in these categories:

(1) <u>Assignment to the Calculation Variable Names the</u>

<u>Value of Zero</u>

(a) All variable names that before pendant impact have the value of zero--such as tape elongation, kink-wave coordinates (angles and distances), arresting-gear motion variables, deck-geometry values, arresting-hook load, tape tensions, etc.--are set equal to zero.

(b) Other variables set equal to zero are TIME, the symmetry flag IFLGSM, the output printer line counter ICOUNT, and the linear array DATUM(32).

(2) <u>Conversion of Units of Input Variables</u>: To simplify the preparation of input values, their units are those of standard, commonly used values. However, to ease calculations through conformity of units, some input values must be converted to units which agree with other variable units. For example, vehicle engaging speed VELENG is normally referred to in knots and is therefore, input this way. For calculations, however, speed in FT/SEC would be more suitable and therefore the conversion is performed.

(3) <u>Calculation of Intermediate Input</u>: Parameter variables that are not part of input but have definite values aside from zero and must be introduced into the main calculation loop, are calculated from input data or companion values. An example is the initial vehicle acceleration VACC, which is computed from the vehicle mass, VMASS, and forces of thrust VTHRUS, arresting-hook load VHOOK, and drag VTDRAG.

### 3. Calculation Section

a. The purpose of this section is to compute prime parameter values as functions of time for output. The parameters that are currently being computed are listed in the output section, page 16.. To compute prime parameter values, many interrelated equations describing

(1) Vehicle distances and motion,

(2) Tape and pendant properties and geometry, and.

(3) Tape-reel rotation and motion

are drawn upon to develop changes of the "key" motion generation parameters, vehicle and reel accelerations, with time. These motion generation parameters are the basis of the calculation loop.

b. <u>Time Generation</u>: The impact of the arresting-hook with the pendant is simulated when the calculation loop is entered for the first time. For each pass through the calculation loop, TIME (arrestment time) is increased by one time calculation increment.

c. <u>Port and Starboard Calculations</u>: Port and starboard parameter values can be calculated separately if the arrestment is OFF-CENTER. If the symmetry flag indicates an ON-CENTER arrestment, calculations are performed for port parameters only and set equal to starboard values for each pass through the loop. (See Appendix C, Program Flow Chart, for more details.)

d. <u>Main Loop Calculations</u>

(1) The main calculation loop is separated into five sections:

(a) Program stop logic,

(b) Port parameter calculations,

(c) Setting of port parameter values to starboard parameter values for a symmetrical arrestment,

(d) Starboard parameter calculations, and

(e) Final calculations.

The port and starboard calculations contain the same equations, differing only by the variable name endings, P for port and S for starboard. Therefore, only the port parameter calculations will be described. Variable names that depict parameter values at the end of a time increment end in the number 2.

(2) Program Stop Logic: Two separate tests are performed upon entrance into the main calculation loop to determine if the program has simulated an arrestment completely and to indicate a halt to program calculations:

(a) Port or starboard two-block: The instantaneous radius of outer wrap of the purchase tape on the reel ROWP is compared to the reel-hub radius RHUB to establish if the tape supply on the reel has been depleted.

(b) Vehicle Speed: The instantaneous vehicle speed VELNST is checked to see if it has reached a value of zero which would indicate the end of an arrestment.

(3) Port Parameter Calculations

(a) Motion calculations: In this section, motion of the vehicle and tape reels is simulated. Speed and velocity (vehicle - VELNS2, reel - RSPP2) are obtained by averaging acceleration values of the beginning (vehicle - VACC, reel - RACP) and end (vehicle - VACC2, reel - RACP2) of the last time increment, multiplying by the time increments, and then by adding this value to the speed/velocity values at the end of the previous increment.(vehicle - VELNST, reel - RSPP). Following this same integration logic, vehicle runout VRUNO2 and reel revolutions RPOP2 are obtained from speed/velocity values. The radius of outer wrap of reel tape ROWP is calculated from the amount of tape that has left the reel. The amount of tape on a reel at any time RLTP is determined by the differences of the total length of tape in system TOLENP and the amount on deck TLENP from the last calculation increment. A new value for tape on deck TLENP2 to account for the motion of vehicle and reels is then computed. See Figure 4 for description of variable names of the runway configuration.

(b) Kink-wave location: The location of the kink-wave in the tape-pendant configuration is established. The velocity of the kink wave is a function of the media in which it is traveling. It is necessary, therefore, to determine for each calculation if the kink wave is traveling through the nylon tape or steel pendant so that the proper dynamic equations describing its motion can be employed. This test is accomplished by checking the three-dimensional distance HYPOTP which is the distance from hook to kink against the length of the pendant on the port side of hook engagement through the use of an IF statement.

(c) Kink-wave velocity:  The kink-wave velocity for either the pendant or tape is calculated.  This velocity is computed in terms of modulus of elasticity (pendant - PENMOD, tape - ETAPEP), longitudinal wave velocity (pendant - CPEND, tape - CTAPEP), and the transverse impact formula approximation (pendant - PENSIG, tape - TASIGP).

(d) Kink-wave three-dimensional coordinate location: The instantaneous location of the kink wave is described by a three-dimensional coordinate system which pinpoints its position by means of angles and linear distances from a fixed reference.  See Figure 5 for an illustrated description of this coordinate system.  Also, the instantaneous arresting-hook elevation HKELEV, the distance of the kink to the tail hook HYPOTP, and the distance of the kink to the runway-edge sheave RESULP, are computed.  See Figure 6 for an illustrated description.

(e) Pendant and tape elongation, tension:  Total elongation of the tape/pendant configuration, DELP, is computed by subtracting the length of the tape/pendant on the runway of the previous time increment, TLENP2 and PLENP, from the new length of the tape/pendant on the runway just established from the three-dimensional distances, HYPOTP and RESULP, and SPLITP.  See Figures 4 and 6.  The tape elongation factor, TELFP, which is the percent tape elongation and is required for substitution into the tape modulus of elasticity equation and the tape tension equation (see pages E-3 and E-4, Appendix E under procedure), is computed by subtracting the pendant elongation PELP from the total elongation DELP, and dividing by the product of the length of tape on the runway TLENP2 and 100.  Tape tension, DTENP, is computed and its values used to calculate a new value of pendant elongation PELP2, which is a function of pendant length PLENP, pendant modulus of elasticity PENMOD, pendant cross-sectional area PENX, and tape tension.

(f) Tape-reel acceleration, arresting-hook load: Tape-reel acceleration RACP2, is determined by the relationship between the torques acting on the reel and rotor and the polar moment of inertia of the reel and rotor.  (See Appendix F for detailed description of equation derivation.)  Arresting-hook load, HOOKP, is established by resolving tape tension into vector components in the direction of hook engagement.  (See Figure 7, page 31 for diagram.)

(g) Test to determine if kink wave has reached the sheave:  At the end of the port parameter calculation section, a test is performed to determine whether the kink wave has reached the runway-edge sheave.  This test is accomplished by comparing XWAVEP, which is the distance from the centerline of engagement to the kink wave, to DHAP, which is the distance from the centerline of engagement to the runway-edge sheave.  When the test indicates that these values are equal, the kink wave has reached the sheave and the three-dimensional coordinates and angles at this time must be recorded in order to establish a new path for the next kink wave to follow.  If the kink wave has reached the sheave, values of GAMAXP, GAMAYP, GAMAZP, XWAVEP, YWAVEP, ZWAVEP, and HYPOTP are computed.

(4) Arresting Symmetry Check: If the symmetry flag IFLGSM indicates an ON-CENTER arrestment and a completely symmetrical system installation (IFLGSM = 0), port parameter values are set equal to starboard parameter values. This procedure minimizes computational time under computer control when the arrestment is symmetrical. If the arrestment is not symmetrical (IFLGSM = 1), the computer is instructed to enter the starboard calculation section. This test is performed by the use of an IF statement.

(5) Final Calculations

(a) In the final calculation section, VACC2, the vehicle acceleration is calculated and parameter variable values that have been calculated in the port and starboard sections (of present time increment) are stored for reuse upon the re-entrance of the main calculation loop.

(b) Vehicle acceleration is obtained simply by applying Newton's second law of motion and using the fundamental equation, Force = mass x acceleration. Vehicle acceleration is equal to the resultant forces acting on it, thrust (VTHRUS), arresting-hook load (VHOOK), and the total drag force (VTDRAG) divided by its mass (VMASS).

(c) Storage of parameter values for use in the next time increment is accomplished by assigning present increment variable values which are suffixed with the number "2", to the same respective variable names not followed by the number "2".

(6) Saving of Maximum Values: The maximum value of certain parameters is required for most arresting test programs. This section provides a means of obtaining maximum values of desired parameters for an arrestment along with the times that the maximum values occurred. Maximum values are designated by the variable name prefixed by the letter "A". The following maximum values are currently being computed for output:

| | |
|---|---|
| arresting-hook load | - AVHOOK |
| tape tension, port | - ADTENP |
| tape tension, stbd | - ADTENS |
| vehicle deceleration | - AVACCG |
| reel velocity, port | - ARSPP |
| reel velocity, stbd | - ARSPS |
| reel acceleration, port | - ARACP |
| reel acceleration, stbd | - ARACS |

(7) Main Calculation Loop Output Storage: All parameter values that are to be output are stored in the linear array DATUM(32) along with the arrestment time TIME(DATUM (9)), and are recorded on tape. The program listing statement 300 (see Appendix A), shows the parameter names along with their assigned array position.

(8) Run Termination: Run termination is based on elapsed time and occurs when the elapsed time (TIME) exceeds a preset arrestment time limit.

(9) Kink-Wave Coordinate Generation: The last section of the main calculation loop generates the three-dimensional kink-wave coordinate values and the kink-wave velocity for both the port and starboard kink waves along with the corresponding time of arrestment.

4. Output Section

a. Program output consists of five parts:

(1) Record of input,

(2) Kink-wave coordinates,

(3) Maximum values,

(4) Vehicle motion parameters, arresting-hook load and tape tensions, and

(5) Port tape and tape-reel values.

b. The record of input data is output on printed form immediately following the initialization section of the program. See Appendix A for a sample output listing.

c. Kink-wave coordinates are current values that are printed after every calculation iteration until the run is terminated. The kink-wave coordinates, XWAVEP(S), YWAVEP(S), and ZWAVEP(S), are printed along with the corresponding arrestment time TIME for both port and starboard kink waves.

d. The remaining outputs are recorded on magentic tape during the program calculation run and are printed after the calculations are completed. The maximum values are printed as explained in Section III, paragraph E.

e. The vehicle motion parameter values that are printed along with the arrestment time are:

| | |
|---|---|
| Speed | - VELNS2 |
| Runout | - VRUNO2 |
| Rolling friction | - VROLL |
| Total drag | - VTDRAG |
| Acceleration | - VACC2 |

Also printed out in this output are:

| | |
|---|---|
| Arresting-hook load | - VHOOK |
| Port tape tension | - DTENP |
| Starboard tape tension | - DTENS |

The port tape and tape-reel values that are printed out are:

| | |
|---|---|
| Tape reel velocity | - RSPPR |
| Tape reel position | - RPOP |
| Tape wrap radius | - ROWP |
| Tape on deck | - TLENP |
| Arresting-hook-point-to-sheave distance | - DLENP |
| Pendant elongation | - PELP |
| Total elongation | - DELP |
| Tape elongation factor | - TELFP |
| Tape tension | - DTENP |
| Tape on reel | - RLTP |
| Total reel inertia | - RTINP |
| Tape-reel acceleration | - RACPR |

## VII DISCUSSION

A. _Run Verification:_ One of the most important parameters associated with arrestment test programs is arresting-hook load. It is, therefore, used as a basis of comparison to determine the general accuracy of a computer mathematical model simulation. During the development stages of the mathematical model, arresting-hook-load values obtained from a computer run are plotted against the arresting-hook-load values of actual test data to give an indication of how well a particular program design logic change has affected the predicted results. Other parameters are, of course, analyzed but the arresting-hook load serves as an index of the overall performance of the model.

B. Current Status of Program Performance

1. At the present stage of development, the program computes all required tape-reel and vehicle parameters for ON or OFF-CENTER arrestments from the time of pendant pickup until the vehicle comes to a stop. However, program logic at this point of development is not complete. The basic logic pieces are present and do account for a complete parameter output, but a need exists for refinement in existing logic pieces and also logic supplementation to further improve the accuracy of the model. The problem that exists is the time of peak value occurrence in arresting-hook-load and tape-tension plotted time histories. Peak values are within $\pm$ 5% of the corresponding actual peaks; however, the model calculates them to occur at earlier times than actual data indicated they occur.

2. The current logic piece that is suspected of being the prime cause for the program's generation of peak values being off in time is the determination of tape tension. Tape tensions are calculated as functions of purchase-tape elongation. An equation is derived that expresses tension in terms of percent elongation of the tape by fitting a curve through actual load-percent elongation data. The problem is that with nylon tape the relationship between tension and percent elongation is hysteretic in nature. If a system could be developed to express the load-percent elongation relationship more adequately, the arresting-system physical parameters could be described more accurately by the program.

3. The following is a list of arrestment phenomena that, up to this point in the development of the model, are not yet included:

a. Tape-reel stack slip

b. Angled arrestments where the aircraft or deadload does not engage the pendant perpendicularly.

c. Arresting-hook slip on pendant during OFF-CENTER or angled arrestments

    d.  Two-block logic which will provide for parameter values after two-block condition.

    e.  Effect that tape/pendant connector has on kink-wave motion

    f.  Pre-tensioning

    g.  Logic that would account for energy and momentum of the arresting system with time

## VIII  PROGRAM USE

A.  <u>Program Deck Construction</u>:  The following illustrates the setup
of a program card deck for a normal run on a CDC 6600 computer:

```
                                    8
                                    9
                              DELTIM, VCOAD, ...
                              VELENG, VWEIGH, ...
                              PENMOD
                              RINP, RINS, ...
                    7         TTHICK, TWGHT, ...
COLUMN 1            8          DKSPAN, SPLITP, ...
                    9
                                              8
                                              9
   INPUT

                    7
      COLUMN 1     8
                    9                   E-28 MATH MODEL
                                                  8
                                                  9
                                              LGO/RFL/
      PROGRAM                               SET(O)
                                              RUN (S......5000)
                                              E28, CM50000, T40, I0400, P6
                    7                         $ CHARGE, N02093J-300
      COLUMN 1     8                                  7
                    9                                 8
                                                      9
      CONTROL CARDS

                          7
        COLUMN 1         8
                          9
```
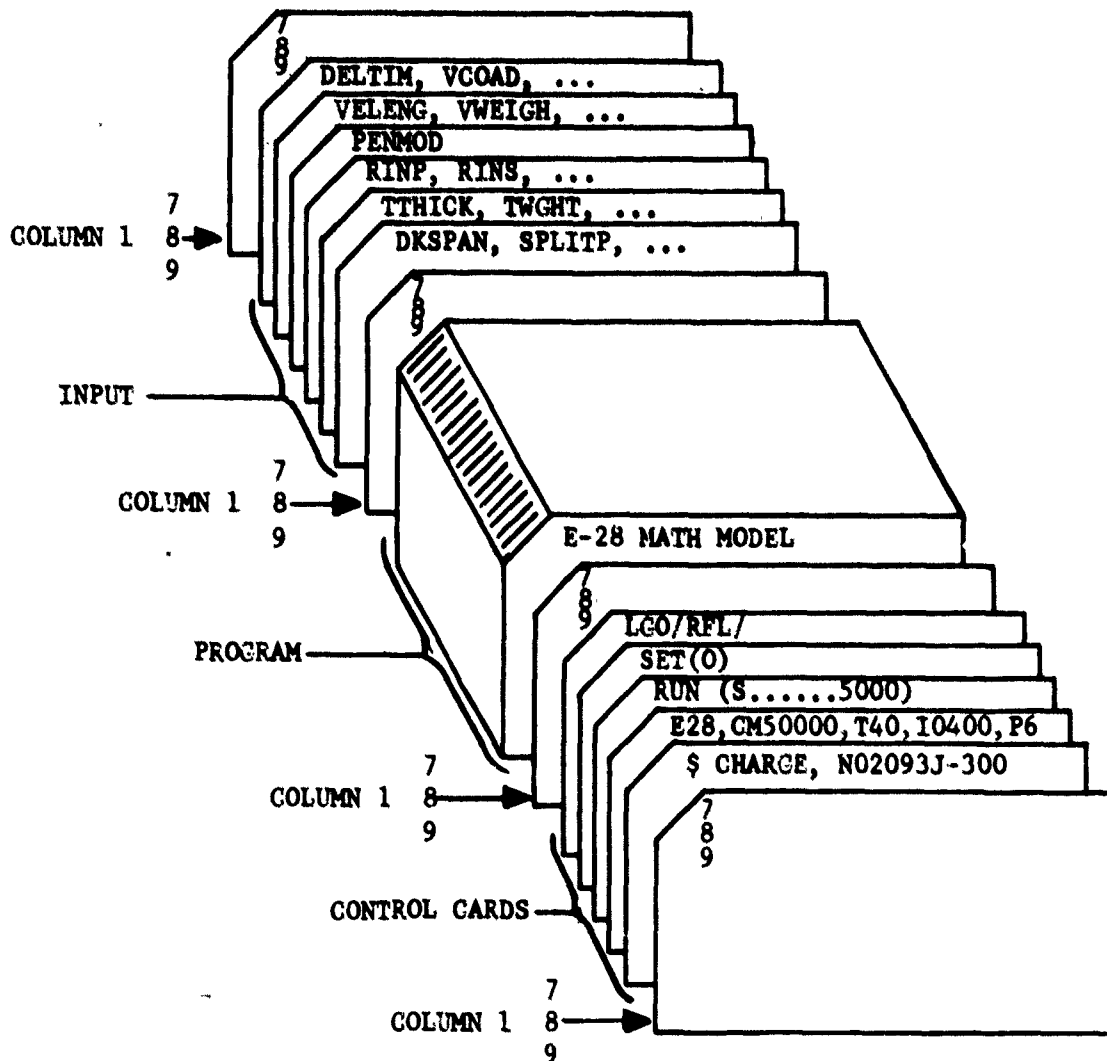
B. **Input Data Preparation:** Program input consists of six cards which are divided into two sections: arresting-gear configuration and event information. The cards are placed at the end of the card deck and are separated from the program by a 7, 8, 9 multiple punched card. The input cards variable name location and format are tabulated below:

| | INPUT CARD ORDER | VARIABLE NAMES | FORMAT |
|---|---|---|---|
| ARRESTING-GEAR CONFIGURA-TION INFORMATION | 1 | DKSPAN, SPLITP, SPLITS, PENLEN, PENX, POFFC PENDEN | 7F10.4 |
| | 2 | TTHICK, TWGHT, TOLENP, TOLENS, C1, C2, C3 | 7F10.4 |
| | 3 | RINP, RINS, BRAKEC, RHUB, BRAKEX, TWIDE | 6F10.4 |
| | 4 | PENMOD | 1F12.2 |
| EVENT INFORMATION | 5 | VELENG, VWEIGH, VTHRUS, WINDKT, BARO, TEMPA | 6F10.4 |
| | 6 | DELTIM, VCOAD, DOFFC, HOOKHI, WHKLEN | 5F10.5 |

Definitions of variable names can be found in Appendix B. Input values should be obtained from the test engineer and/or the Computer Division.

C. **Control Card Preparation:** There are five control cards which preceed the program in the card deck and are separated from it by a 7, 8, 9 multiple punched card.

1. **Charge Card:** This card is used for accounting purposes:

```
$ CHARGE, aaaaa C1C2 - UUU
  aaaaa = five-digit charge number
  C1C2  = two check digits
  -     = indicates subcharge number
  UUU   = three-digit subcharge number (optional)
```

2. **Scope Job Card:** The parameters of this card describe the job's priority, time limits, memory, and peripheral equipment requirements. All parameters are octal values:

```
Job Name  (CMfl, Tt, IO, Pp)

Job Name = To provide user identification of this job.
CMfl     = Loading field length, which specifies the amount
           of memory needed to obtain a control point and
           load the program into memory.
Tt       = Central processor time limit for the job in seconds;
           a maximum of five octal digits.
IO       = Input/Output time limit in seconds.
Pp       = Priority level (P) at which job enters the system.
```

3. <u>Run Card</u>: The FORTRAN compiler is called by this card:

> RUN (cm, fl, bl, if, of, rf, lc)
> Only two parameters are required, cm and lc, the rest are omitted
> cm = Compiler mode option
> lc = Line-limit (octal) on the output file of the object program

4. <u>Set zero card</u>: This card sets equal to zero all storage locations containing variable names and arrays:

> SET (0)

5. <u>Execute Card</u>: This card loads the program into memory and begins execution:

> LGO/RFL
> LGO = Load and go
> RFL = Request field length - an option that allows optional usage of central memory

For more detailed information on preparing the control cards, see references (c) and (d) or consult a programmer from the Computer Division.

IX  FUTURE WORK

A.  Continued development on the model will be directed to the following areas:

      a.  Hysteresis representation of the tape modulus of elasticity

      b.  On-center and off-center angled arrestments

      c.  Tape stack slip

B.  Also, at present, the program outputs data in tabulation form. Plot capabilities should be added to the program.

X REFERENCES

(a) F. O. Ringleb, NAEC Engineering Department Report No. NAEC-ENG-6169 of 27 Dec 1956:   Cable Dynamics

(b) F. O. Ringleb, "Basic problems in the dynamics of the aircraft arresting gear", A Decade of Basic and Applied Science in the Navy, Washington, D.C., 1957

(c) Control Data, 6400/6500/6600 Computer Systems, Scope 3 Reference Manual (Up to Revision J)

(d) Control Data, 6400/6500/6600 Computer Systems, Fortran Reference Manual (Up to Revision C)
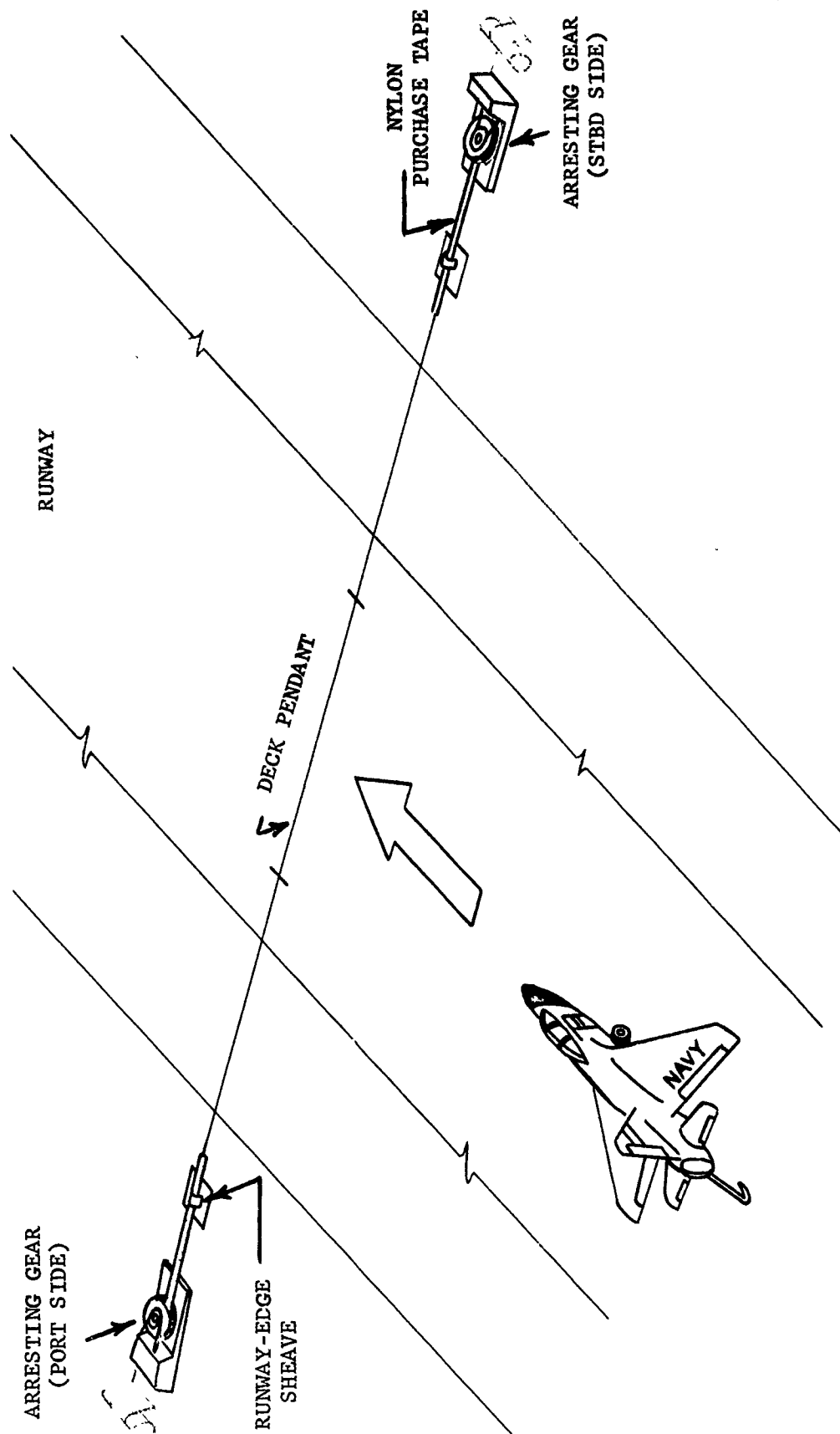
Figure 1 - Typical Shorebased Arresting-Gear Installation Simulated by the E-28 Mathematical Model
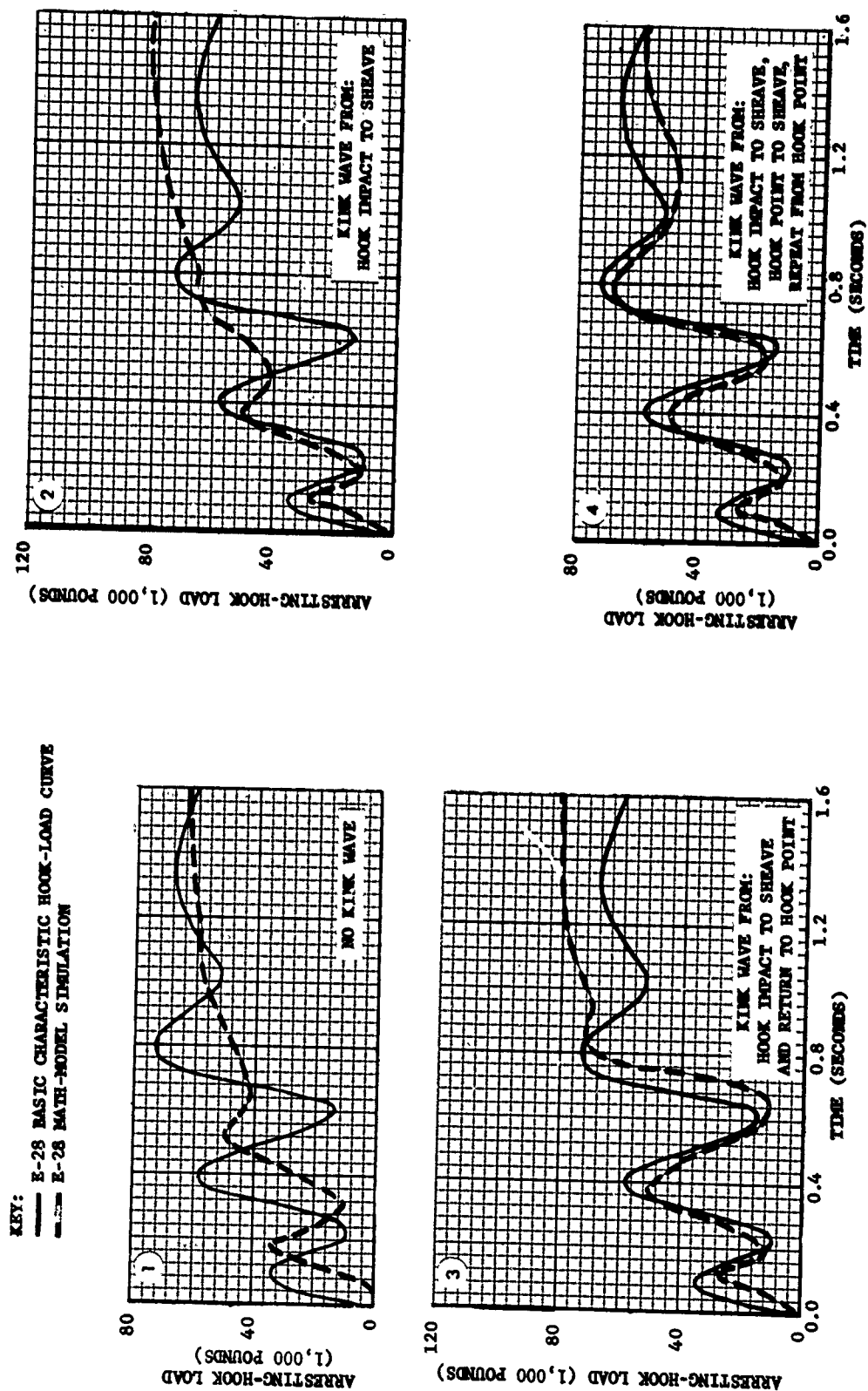
Figure 2 - Arresting-Hook-Load Time Histories of Various E-28 Math-Model Kink-Wave Designs Compared to a Basic Characteristic Hook-Load Curve

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## ARRESTING-GEAR CONFIGURATION (INPUT VALUES)

| PARAMETER NAME | FORTRAN SYMBOL | VALUE | UNITS |
|---|---|---|---|
| DECK SPAN | DKSPAN | 164.000 | FT |
| PENDANT LENGTH | PENLEN | 154.000 | FT |
| PENDANT MODULUS OF ELAS. | PENMOD | 1872000000.000 | LB/FT-SQ |
| PENDANT AREA | PENX | .009 | FT-SQ |
| PENDANT DENSITY | PENDEN | 17.890 | LB $SEC^2/FT^4$ |
| PORT SPLIT DISTANCE | SPLITP | 49.000 | FT |
| PORT TAPE LENGTH | TOLENP | 840.000 | FT |
| PORT REEL INERTIA (METAL) | RINP | 114.000 | SLUG FT-SQ |
| BRAKE CONSTANT | BRAKEC | 12.310 | NONE |
| TAPE LOAD-% ELONG.COEFF. | C1 | 1.709 | NONE |
| TAPE LOAD-% ELONG.COEFF. | C2 | 85.367 | NONE |
| TAPE LOAD-% ELONG.COEFF. | C3 | 4019.790 | NONE |
| PENDANT OFF-CENTER DISTANCE | POFFC | 0.000 | FT |
| PURCHASE TAPE THICKNESS | TTHICK | .344 | IN. |
| PURCHASE TAPE WEIGHT/FOOT | TWGHT | 1.000 | LB/FT |
| PURCHASE TAPE WIDTH | TWIDE | 8.000 | IN. |
| PURCHASE TAPE AREA | TAREA | 2.752 | IN.-SQ |
| STBD SPLIT DISTANCE | SPLITS | 49.000 | FT |
| STBD TAPE LENGTH | TOLENS | 840.000 | FT |
| STBD REEL INERTIA (METAL) | RINS | 114.000 | SLUG FT-SQ |
| BRAKE EXPONENT | BRAKEX | 2.000 | NONE |
| HUB RADIUS | RHUB | 9.000 | IN. |

## EVENT INFORMATION (INPUT VALUES)

| | | | |
|---|---|---|---|
| VEHICLE ENGAGING SPEED | VELENG | 150.000 | KN |
| VEHICLE WEIGHT | VWEIGH | 53000.000 | LB |
| VEHICLE THRUST | VTHRUS | 0.000 | LB |
| HEAD WIND | WINDKT | 0.000 | KN |
| BAROMETRIC PRESSURE | BARO | 30.000 | IN. HG A |
| AMBIENT TEMPERATURE | TEMPA | 68.000 | DEG F |
| CALCULATION INCREMENT | DELTIM | .001 | SEC |
| AERO DRAG COEFFICIENT | VCOAD | .041 | LB $SEC^2/FT^2$ |
| DECK OFF-CENTER DISTANCE | DOFFC | 0.000 | FT |
| ARRESTING-HOOK HEIGHT | HOOKHI | 2.313 | FT |
| ARRESTING-HOOK LENGTH | VHKLEN | 6.167 | FT |

Figure 3 - Sample Output of Input
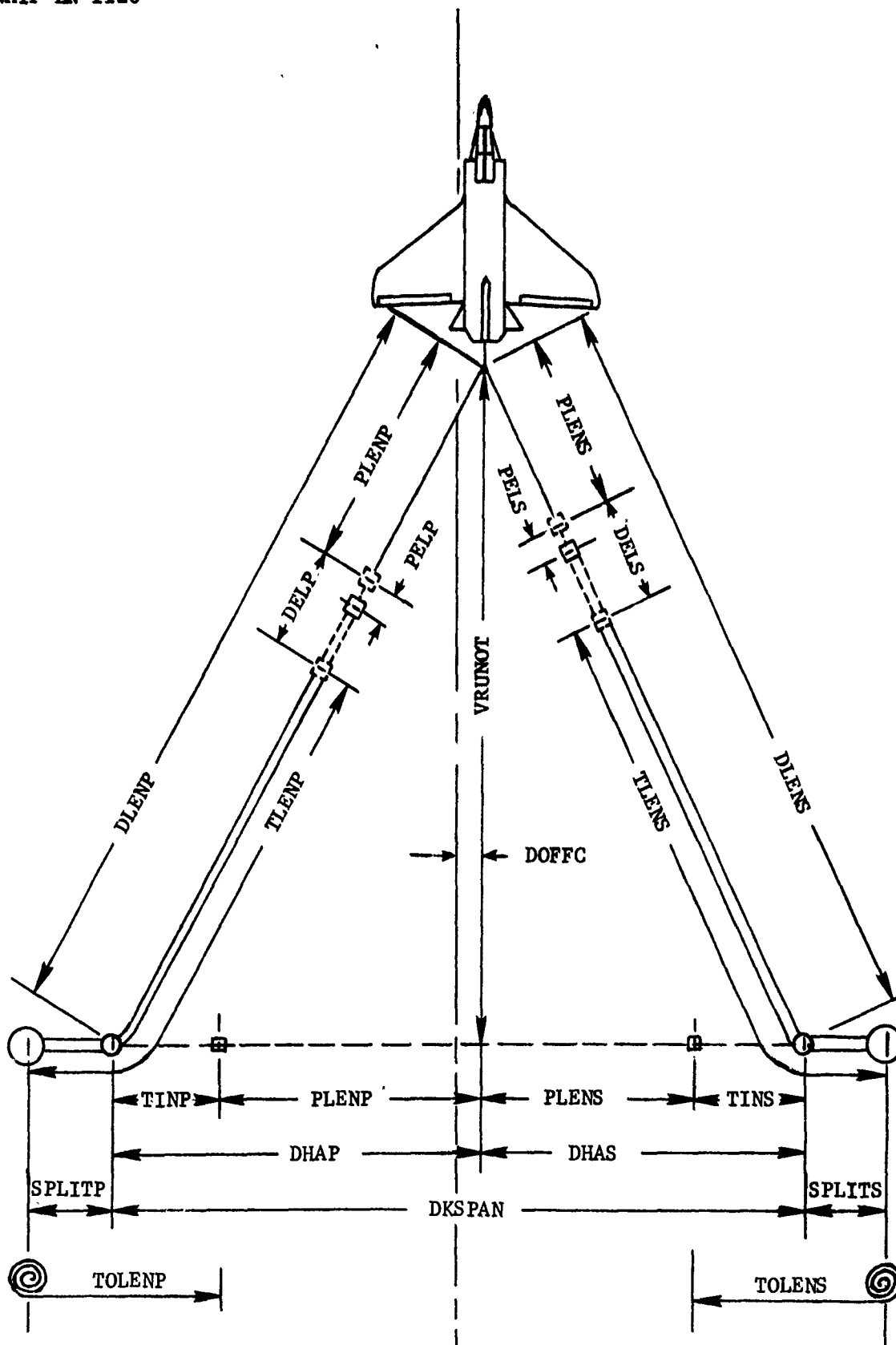
Figure 4 - Schematic of Runway Installation With Variable Name Descriptions

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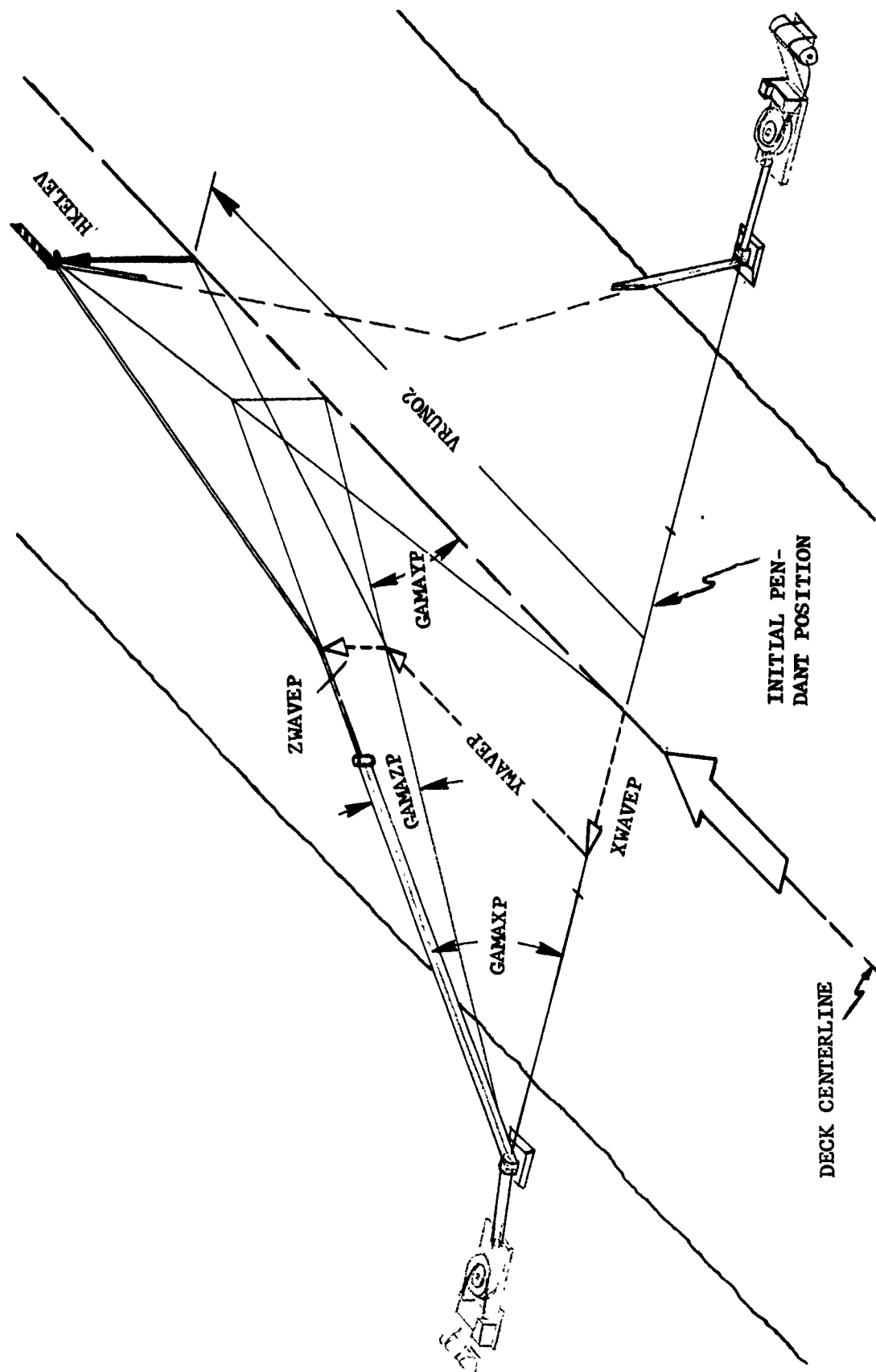
Figure 5 - Three-Dimensional Kink-Wave Coordinates
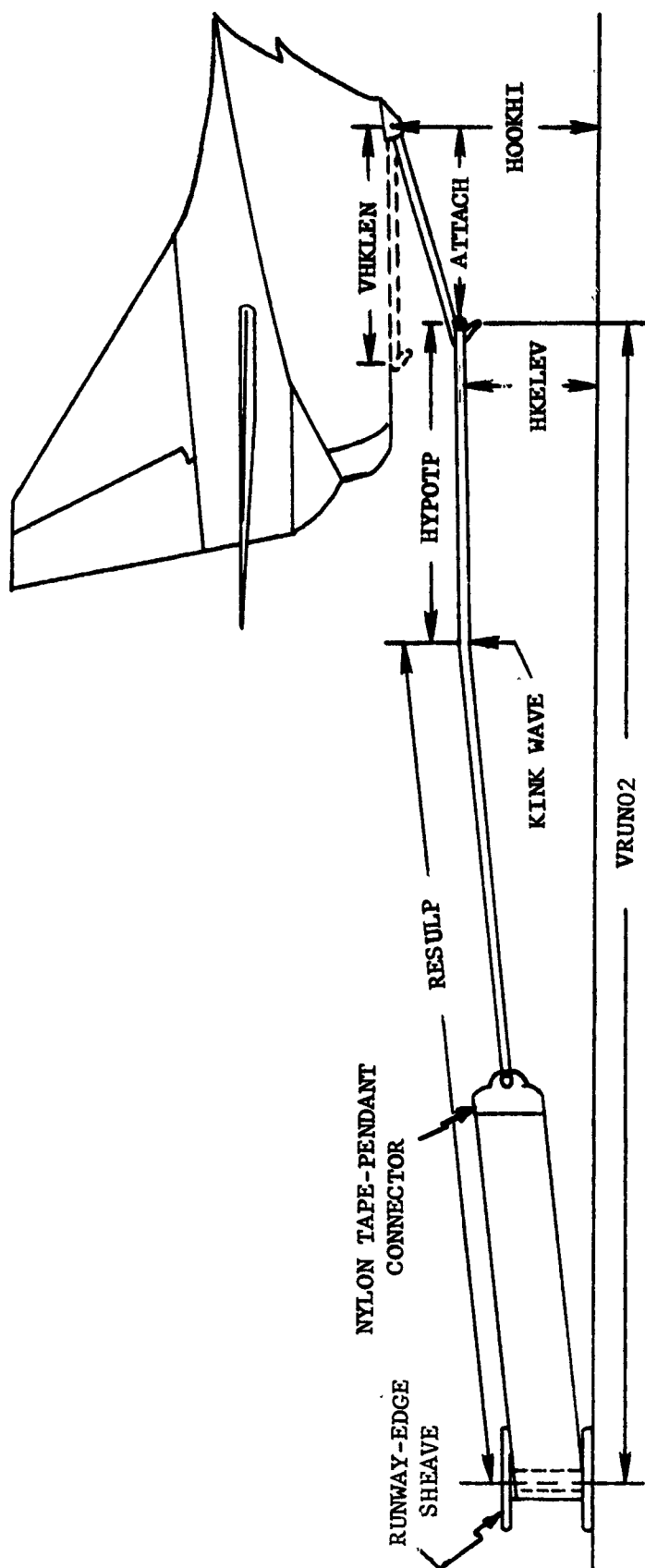
Figure 6 - Runway and Arresting-Hook Measurements

HOOK LOAD = HOOKP = DTENP x COS θ

A = HKELEV - ZWAVEP

B = VRUNO2 - YWAVEP

C = $\sqrt{A^2 + B^2}$

D = XWAVEP

θ = TAN$^{-1}$ (D/C)
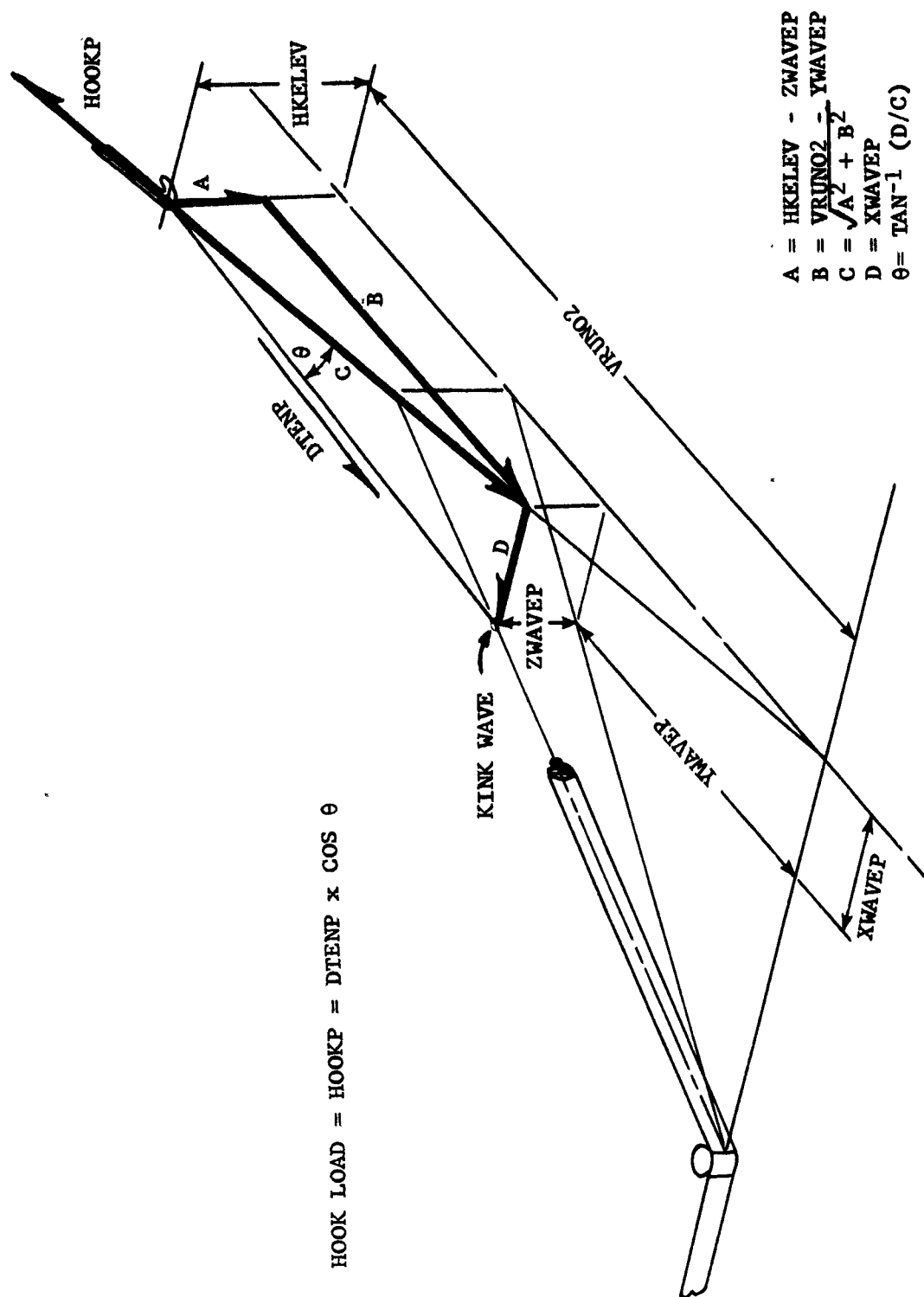
Figure 7 - Arresting-Hook Load Determination (Port Side Component Breakdown)

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APPENDIX A - MATHEMATICAL PERFORMANCE PREDICTION MODEL PROGRAM LISTING

```
THIS PROGRAM WAS REDESIGNED TO REFLECT A REVISED APPROACH. NEW           1
LOGIC INCLUDES A 3-DIMENSIONAL KINK WAVE FORM, INCREMENTAL COMPUT-       2
ATION OF THE KINK VELOCITY TO ACCOUNT FOR THE VARYING MODULUS OF         3
ELASTICITY OF THE NYLON TAPE AND LOCATION OF THE KINK (I.E. IN           4
TAPE OR STEEL PENDANT); AND NEW LOGIC FOR KINK2 WHICH ASSUMES THE        5
FORMATION OF A NEW KINK EMINATING FROM THE HOOK AS KINK1 IMPACTS         6
THE SHEAVE.                                                              7
      DIMENSION DATUM(32)                                                8
      READ IN ALL DATA PERTINENT TO THE ARRESTING GEAR CONFIGURATION     9
      JGEOR = 0                                                         10
    1 READ 2, DKSPAN, SPLITP, SPLITS, PENLEN, PENX, POFFC, PENDEN       11
      READ 2, TTHICK, TWGHT, TOLENP, TOLENS, C1, C2, C3                 12
      READ 3, RINP, RINS, BRAKEC, RHUB, BRAKEX, TWIDE                   13
      READ 4, PENMOD                                                    14
    2 FORMAT (7F10.4)                                                   15
    3 FORMAT (6F10.4)                                                   16
    4 FORMAT (1F12.2)                                                   17
    5 FORMAT (5F10.5)                                                   18
      READ IN ALL DATA PERTINENT TO EVENT INFORMATION                   19
      READ 3, VELENG, VWEIGH, VTHRUS, WINDKT, BARO, TEMPA               20
      READ 5, DELTIM, VCOAD, DOFFC, HOOKHI, VHKLEN                      21
      INITIALIZATION OF VARIABLES                                       22
      IGL = 0                                                           23
      DTENP=BTENS=RSPPR=RSPSR=0.0                                       24
      DELP=DELS=RACPR=RACSR=0.0                                         25
      VKINKP=VKINKS=0.0                                                 26
      VRUNOT=RSPP=RSPS=RACP=RACS=RPOP=RPOS=RELP2=PELS2=RACP2=RACS2=0.0  27
      AVHOOK = ADTENP = ADTENS = AVRCCG = ARSPP = ARSPS =RRACP=RRACS=0.0 28
      XWAVEP = YWAVEP = ZWAVEP = XWAVES = YWAVES = ZWAVES = 0.0         29
      ICOUNT = 0.0                                                      30
      TIME = 0.0                                                        31
      VMASS = VWEIGH / 32.174                                           32
      THDEI = DELTIM / 2.0                                              33
      WINDFT = WINDKT * 1.6878                                          34
      VELNST = VELENG * 1.6878                                          35
      VROLL = .00045 * VELENG * VWEIGH                                  36
      DRAGK = 17.3262 * ( BARO / ( TEMPA + 459.4 )) * VCOAD             37
      VADRAG = (VELNST + WINDFT)**2 * DRAGK                             38
      VTDRAG = VADRAG + VROLL                                           39
      HOOKP = HOOKS = 0.0                                               40
      VHOOK = HOOKP * HOOKS                                             41
      VACC=VACC2=(VTHRUS-VHOOK-VTDRAG)/VMASS                            42
      VACCG = VACCG / 32.174                                            43
      HYPOTP = HYPOTS = 0.0                                             44
      TELFP = TELFS = 0.0                                               45
      PELP2 = 0.0                                                       46
      GAMAYP = GAMAYS = 1.5708                                          47
      GAMAXP = GAMAZP = GAMAXS = GAMAZS = 0.0                           48
      ATTACH = SQRT (VHKLEN **2 - HOOKHI **2)                           49
      DHAP = .5 * DKSPAN * DOFFC                                        50
```

```
      DHAS = .5 * DKSPAN - DOFFC                                       51
      DLENP = DHAP                                                     52
      DLENS = DHAS                                                     53
      TINP = .5 * (DKSPAN - PENLEN ) + POFFC                           54
      TINS = .5 * (DKSPAN - PENLEN ) - POFFC                           55
      PLENP = DHAP - TINP                                              56
      PLENS = DHAS + TINS                                              57
      TLENOP = TLENP * SPLITP + TINP                                   58
      TLENOS = TLENS * SPLITS + TINS                                   59
      RLTP = TOLENP - TLENP                                            60
      RLTS = TOLENS - TLENS                                            61
      RNUIP  = ((-TTHICK - 2*RHUB + SQRT ((TTHICK + 2*RHUB)**2 +       62
     1( 4 * TTHICK * (( TOLENP - TLENP ) * 12)/3.1416 )))/ (2*TTHICK)  63
      ROWP   = RHUB +(TTHICK * RNUIP)                                  64
      RNUIS  = ((-TTHICK - 2*RHUB + SQRT ((TTHICK + 2*RHUB)**2 +       65
     1( 4 * TTHICK * (( TOLENS - TLENS ) * 12)/3.1416 )))/ (2*TTHICK)  66
      ROWS   = RHUB + (TTHICK * RNUIS)                                 67
      CA     = TTHICK / 6.2832                                         68
      PEAP   = PLENP / (PENMOD * PENX)                                 69
      PEAS   = PLENS / (PENMOD * PENX)                                 70
      CD     = ( RHUB / 12.0 )**2                                      71
      CE     = TWGHT / 64.348                                          72
      LTCONT = 0                                                       73
      TAREA = TTHICK * TWIDE                                           74
      IO = 0                                                           75
      DATUM(32) = 0.0                                                  76
      JTIME = 1                                                        77
      TAPDEN = TWGHT/(32.17*(TAREA/144.0))                             78
      TEST FOR ON CENTER ENGAGEMENT AND SYMETRICAL A.G. CONFIGURATION  79
      IFLGSM = 0                                                       80
      JSYMVP = DHAP*TINP*SPLITP*TOLENP*RINP                            81
      JSYMVS = DHAS*TINS*SPLITS*TOLENS*RINS                            82
      IF(JSYMVP-JSYMVS)19,18,19                                        83
   18 IFLGSM = 1                                                       84
   19 CONTINUE                                                         85
   20 FORMAT(1H1,///46X,28HARRESTING GEAR CONFIGURATION)               86
   21 FORMAT (/28X,7HFORTRAN,52X,7HFORTRAN)                            87
   22 FORMAT(6X,14HPARAMETER NAME,8X,6HSYMBOL,8X,5HVALUE,3X,5HUNITS,11X, 88
     114HPARAMETER NAME,8X,6HSYMBOL,8X,5HVALUE,3X,5HUNITS)             89
   23 FORMAT(/10H DECK SPAN,18X,6HDKSPAN,1X,F14.3,1X,2HFT,9X,24HPENDANT 90
     1OFF CENTER DIST.,3X,5HPOFFC,2X,F14.3,1X,2HFT)                    91
   24 FORMAT (15H PENDANT LENGTH,13X,6HPENLEN,1X,F14.3,1X,2HFT,9X,23HPUR 92
     1CHASE TAPE THICKNESS,4X,6HTTHICK,1X,F14.3,1X,2HIN)               93
   25 FORMAT (25H PENDANT MODULUS OF ELAS.,3X,6HPENMOD,1X,F14.3,1X,8HLB/ 94
     1FT-SQ,3X,25HPURCHASE TAPE WEIGHT/FOOT,2X,5HTWGHT,2X,F14.3,1X,5HLB/ 95
     2FT)                                                              96
   26 FORMAT (13H PENDANT AREA,15X,4HPENX,3X,F14.3,1X,5HFT-SQ,6X,19HPURC 97
     1HASE TAPE WIDTH,8X,5HTWIDE,2X,F14.3,1X,2HIN)                     98
   27 FORMAT (16H PENDANT DENSITY,12X,6HPENDEN,1X,F14.3,11HLB SEC2/FT4,  99
     11X,18HPURCHASE TAPE AREA,9X,5HTAREA,2X,F14.3,1X,5HIN-SQ)         100
```

```
28 FORMAT (20H PORT SPLIT DISTANCE,8X,6HSPLITP,1X,F14.3,1X,2HFT,9X,      101
   119HSTBD SPLIT DISTANCE,8X,6HSPLITS,1X,F14.3,1X,2HFT)                 102
29 FORMAT (17H PORT TAPE LENGTH,11X,6HTOLENP,1X,F14.3,1X,2HFT,9X,        103
   116HSTBD TAPE LENGTH,11X,6HTOLENS,1X,F14.3,1X,2HFT)                   104
30 FORMAT (26H PORT REEL INERTIA (METAL),2X,4HRINP,3X,F14.3,1X,          105
   110HSLUG FT-SQ,1X,25HSTBD REEL INERTIA (METAL),2X,4HRINS,3X,          106
   2F14.3,1X,10HSLUG FT-SQ)                                              107
31 FORMAT (15H BRAKE CONSTANT,13X,6HBRAKEC,1X,F14.3,1X,4HNONE,7X,        108
   114HBRAKE EXPONENT,13X,6HBRAKEX,1X,F14.3,1X,4HNONE)                   109
32 FORMAT (25H TAPE LOAD-xELONG. COEFF.,3X,2HC1,5X,F14.3,1X,4HNONE,      110
   17X,10HHUB RADIUS,17X,4HRHUB,3X,F14.3,1X,2HIN)                        111
33 FORMAT (25H TAPE LOAD-xELONG. COEFF.,3X,2HC2,5X,F14.3,1X,4HNONE)      112
34 FORMAT(25H TAPE LOAD-(FLONG. COEFF.,3X,2HC3,5X,F14.3,1X,4HNONE,7X,    113
   125HARRESTMENT IS SYMMETRICAL)                                        114
35 FORMAT(///51X,17HEVENT INFORMATION)                                  115
36 FORMAT(/32X,14HPARAMETER NAME,10X,6HSYMBOL,8X,5HVALUE,3X,5HUNITS)     116
37 FORMAT(/29X,25HVEHICLE ENGAGING VELOCITY,2X,6HVELENG,1X,F14.3,1X,     117
   15HKNOTS)                                                             118
38 FORMAT(29X,14HVEHICLE WEIGHT,13X,6HVWEIGH,1X,F14.3,1X,3HLBS)          119
39 FORMAT(29X,14HVEHICLE THRUST,13X,6HVTHRUS,1X,F14.3,1X,3HLBS)          120
40 FORMAT(29X,8HHEADWIND,19X,6HWINDKT,1X,F14.3,1X,5HKNOTS)               121
41 FORMAT(29X,19HBAROMETRIC PRESSURE,8X,4HBARO,3X,F14.3,1X,7HIN HG A)    122
42 FORMAT(29X,19HAMBIENT TEMPERATURE,8X,5HTEMPA,2X,F14.3,1X,5HDEG F)     123
43 FORMAT(29X,21HCALCULATION INCREMENT,6X,6HDELTIM,1X,F14.3,1X,3HSEC)    124
44 FORMAT(29X,21HAERO DRAG COEFFICIENT,6X,5HVCOAD,2X,F14.3,1X,11HLB S    125
   1EC2/FT2)                                                             126
45 FORMAT(29X,24HDECK OFF CENTER DISTANCE,3X,5HDOFFC,2X,F14.3,1X,2HFT    127
   1)                                                                    128
46 FORMAT(29X,15HTAILHOOK HEIGHT,12X,6HHOOKHI,1X,F14.3,1X,2HFT)          129
47 FORMAT(29X,15HTAILHOOK LENGTH,12X,6HVHKLEN,1X,F14.3,1X,2HFT)          130
48 FORMAT(25H TAPE LOAD-(FLONG. COEFF.,3X,2HC3,5X,F14.3,1X,4HNONE,7X,    131
   129HARRESTMENT IS NOT SYMMETRICAL)                                    132
   PRINT 20                                                              133
   PRINT 21                                                              134
   PRINT 22                                                              135
   PRINT 23,DKSPAN,POFFC                                                 136
   PRINT 24,PENLEN,TTHICK                                                137
   PRINT 25,PENMOD,TWGHT                                                 138
   PRINT 26,PENX,TWIDE                                                   139
   PRINT 27,PENDEN,TAREA                                                 140
   PRINT 28,SPLITP,SPLITS                                                141
   PRINT 29,TOLENP,TOLENS                                                142
   PRINT 30,RINS,RINP                                                    143
   PRINT 31,BRAKEC,BRAKEX                                                144
   PRINT 32,C1,RHUB                                                      145
   PRINT 33,C2                                                           146
   IF(IFLGSM.EQ.1)49,50                                                  147
49 PRINT 34,C3                                                           148
   GO TO 51                                                              149
50 PRINT48,C3                                                            150
```

```
 51 PRINT 35                                                              151
    PRINT 36                                                              152
    PRINT 37,VELENG                                                       153
    PRINT 38,VWEIGH                                                       154
    PRINT 39,VTHRUS                                                       155
    PRINT 40,WINDKT                                                       156
    PRINT 41,BARO                                                         157
    PRINT 42,TEMPA                                                        158
    PRINT 43,DELTIM                                                       159
    PRINT 44,VCOAD                                                        160
    PRINT 45,DOFFC                                                        161
    PRINT 46,HOOKHI                                                       162
    PRINT 47,VHKLEN                                                       163
    PRINT 88                                                              164
 88 FORMAT ( 1H1, 32X, 55HPORT AND STARBOARD KINK WAVE COORDINATES AND    165
   1 VELOCITIES)                                                          166
    PRINT 89                                                              167
 89 FORMAT ( 1H0, 11X, 6HPORT-X, 4X, 6HPORT-Y, 4X, 6HPORT-Z, 4X,          168
   1 6HVKINKP, 5X, 4HTIME, 15X, 6HSTBD-X, 4X, 6HSTBD-Y, 4X, 6HSTBD-Z,     169
   2 4X, 6HVKINKS, 5X, 4HTIME)                                            170
    PRINT 90 , XWAVEP, YWAVEP, ZWAVEP, VKINKP, TIME, XWAVES, YWAVES,      171
   1 ZWAVES, VKINKS, TIME                                                 172
 90 FORMAT ( 10X, 5F10.3, 10X, 5F10.3)                                    173
    DATUM(1)=VELNSTSDATUM(9) =TIME SDATUM(17)=TELFPSDATUM(25)=DLENS       174
    DATUM(2)=VRUNOTSDATUM(10)=RSPPRSDATUM(18)=RLTP SDATUM(26)=PELS2       175
    DATUM(3)=VHOOK SDATUM(11)=RPOP SDATUM(19)=RTINPSDATUM(27)=DELS        176
    DATUM(4)=VROLL SDATUM(12)=ROWP SDATUM(20)=RACPRSDATUM(28)=TELFS       177
    DATUM(5)=VTDRAGSDATUM(13)=TLENPSDATUM(21)=RSPSRSDATUM(29)=RLTS        178
    DATUM(6)=DTENP SDATUM(14)=DLENPSDATUM(22)=RPOS SDATUM(30)=RTINS       179
    DATUM(7)=DTENS SDATUM(15)=PELP2SDATUM(23)=ROWS SDATUM(31)=RACSR       180
    DATUM(8)=VACCG SDATUM(16)=DELP SDATUM(24)=TLENSSDATUM(32)=0.0         181
    WRITE (7) DATUM                                                       182
    MAIN COMPUTATION LOOP BEGINS AT STATEMENT 100                         183
 99 CONTINUE                                                              184
100 LTCONT = LTCONT + 1                                                   185
    TIME = DELTIM * LTCONT                                                186
    TEST FOR PORT TWO-BLOCK                                               187
    IF ( RHUB .LE. ROWP ) 101,1000                                        188
    TEST FOR STBD TWO-BLOCK                                               189
101 IF ( RHUB .LE. ROWS ) 102,1000                                       190
    TEST FOR INSTANTANEOUS VEHICLE VELOCITY = 0                           191
102 IF ( VELNST .LE. 0.0 ) 1000, 103                                     192
    STATEMENT 103 BEGINS PORT CALCULATIONS                               193
103 VELNS2 = VELNST + THDEL * (VACC + VACC2)                             194
    VRUNO2 = VRUNOT + THDEL * (VELNST + VELNS2)                          195
    RSPP2  = RSPP   + THDEL * (RACP  + RACP2 )                           196
    RPOP2  = RPOP   + THDEL * (RSPP  + RSPP2)                            197
    ROWP2  = ROWP   + CA    * (RPOP  + RPOP2)                            198
    RLTP = TOLENP - TLENP                                                199
    TLENP2 = TLENP  - ROWP2 * (RPOP  - RPOP2 )  / 12.0                   200
```

```
      IF ( HYPOTP.GE.PLENP) 104,105                                       201
  104 IF(TELFP.LE..50)TELFP = .50                                         202
      ETAPFP = -160.635*TELFP**2 + 4079800.0*TELFP - 1919200.0           203
      CTAPEP = SQRT  (ETAPEP / TAPDEN )                                  204
      TASIGP = .5 ** .667 * (VELNS2 / CTAPEP ) ** 1.33                   205
      VKINKP = CTAPEP * (SQRT (TASIGP)+ TASIGP) -(TLENP2 - TLENP) /      206
     1 DELTIM                                                            207
      GO TO 106                                                         208
  105 PENMOD = PENMOD                                                    209
      CPEND = SQRT  ( PENMOD / PENDEN)                                   210
      PENSIG = .5 ** .667 * ( VELNS2 / CPEND ) ** 1.33                   211
      VKINKP = CPEND * (SQRT (PENSIG) - PENSIG) - (TLENP2 - TLENP ) /    212
     1 DELTIM                                                            213
  106 XWAVEP = XWAVEP + (VKINKP * DELTIM * COS  ( GAMAXP )                214
      YWAVEP = YWAVEP - (VKINKP * DELTIM * COS  ( GAMAZP) *COS (GAMAYP)) 215
      ZWAVEP= ZWAVEP = (VKINKP * DELTIM * SIN ( GAMAZP))                 216
      HKELEV = HOOKHI - VHKLEN * COS (1.5708-ATAN (HOOKHI/(ATTACH +      217
     1 VRUNO2)))                                                         218
      HYPOTP = SQRT  (XWAVEP**2+ (VRUNO2-YWAVEP)**2+ (HKELEV-ZWAVEP)**2) 219
      RESULP = SQRT  ((DHAP - XWAVEP)**2 + YWAVEP**2 + ZWAVEP**2)        220
      DLENP  = HYPOTP + RESULP                                           221
      DELP   = HYPOTP + RESULP + SPLITP - TLENP2 - PLENP                 222
      IF ( DELP .LT. 0 )107,108                                          223
  107 DELP = 0.0                                                         224
  108 PELP  = PELP2                                                      225
      TELFP = (DELP - PELP ) / TLENP2 * 100.0                            226
      IF ( TELFP  .LE.  0 ) 109,110                                      227
  109 DTENP = TELFP = PELP2 = 0.0                                        228
  110 DTENP = C1 * TELFP **3 + C2 * TELFP **2 + C3 * TELFP               229
      IF (DTENP.LT. 0)      DTENP = 0                                    230
      PELP2 = PEAP  * DTENP                                              231
      RTINP = RINP + CE * (TOLENP - TLENP2 )*( CD + ( ROWP2 / 12.0)**2)  232
      RACP  = RACP2                                                      233
      RACP2 = (DTENP * ROWP2 / 12.0 - BRAKEC * RSPP2**BRAKEX) / RTINP    234
      HOOKP = DTENP*COS  ( ATAN ( XWAVEP / SQRT  (( HKELEV+ZWAVEP)       235
     1 **2 + (VRUNO2 -YWAVEP) **2 )))                                    236
      ALL PORT CALCULATIONS DONE - TEST NEXT FOR KINK WAVE LOCATION      237
      IF(XWAVEP.GE.DHAP)111,1112                                         238
  111 GAMAXP = ATAN  ( SQRT  ( HKELEV**2 + VRUNO2**2)/XWAVEP)            239
      GAMAYP = ATAN  ( XWAVEP / VRUNO2 )                                 240
      GAMAZP = ATAN  ( HKELEV / SQRT  ( VRUNO2**2 + XWAVEP**2 ))         241
      XWAVEP = 0.0                                                       242
      YWAVEP = VRUNO2                                                    243
      ZWAVEP = HKELEV                                                    244
      HYPOTP = 0.0                                                       245
 1112 IF(IFLGSM.EQ.0)112,1111                                            246
 1111 RSPS2 = RSPP2                                                      247
      RPOS2 = RPOP2                                                      248
      ROWS2 = ROWP2                                                      249
      RLTS = RLTP                                                        250
```

```
      TLENS2 = TLENP2                                                    251
      VKINKS = VKINKP                                                    252
      XWAVFS = XWAVEP                                                    253
      YWAVFS = YWAVEP                                                    254
      ZWAVFS = ZWAVEP                                                    255
      DLENS = DLENP                                                      256
      DELS = DELP                                                        257
      TELFS = TELFP                                                      258
      DTENS = DTENP                                                      259
      PELS2 = PELP2                                                      260
      RACS2 = RACP2                                                      261
      HOOKS = HOOKP                                                      262
      GAMAXS = GAMAXP                                                    263
      GAMAYS = GAMAYP                                                    264
      GAMA7S = GAMAZP                                                    265
      GO TO 130                                                          266
C     STATEMENT 112 BEGINS STARBOARD CALCULATIONS                       267
  112 RSPS2  = RSPS  + THDEL + ( RACS + RACS2 )                         268
      RPOS2  = RPOS  + THDEL + ( RSPS + RSPS2 )                         269
      ROWS2  = ROWS + CA    + ( RPOS - RPOS2 )                          270
      RLTS = TOLENS - TLENS                                             271
      TLENS2 = TLENS - ROWS2 + ( RPOS - RPOS2 ) / 12.0                  272
      IF (HYPOTS .GE. PLENS) 113,114                                    273
  113 IF(TELFS.LE..50)TELFS = .50                                       274
      ETAPFS = -160.635*TELFS**2 + 4079800.0*TELFS - 1919200.0          275
      CTAPFS = SQRT (ETAPFS / TAPDEN)                                   276
      TASIGS = .5 ** .667 * (VELNS2 / CTAPFS ) ** 1.33                  277
      VKINKS = CTAPFS *(SQRT (TASIGS)- TASIGS) - (TLENS2 - TLENS) /     278
     1DELTIM                                                            279
      GO TO 115                                                         280
  114 PENMOD = PENMOD                                                   281
      CPEND  = SQRT ( PENMOD / PENDEN )                                 282
      PENSIG = .5 ** .667 * ( VELNS2 / CPEND ) ** 1.33                  283
      VKINKS = CPEND * (SQRT (PENSIG) - PENSIG) - (TLENS2 + TLENS ) /   284
     1DELTIM                                                            285
  115 XWAVFS = XWAVES + (VKINKS + DELTIM * COS ( GAMAXS ))              286
      YWAVFS = YWAVES - (VKINKS + DELTIM * COS  (GAMAZS) * COS (GAMAYS))287
      ZWAVES = ZWAVES - (VKINKS + DELTIM + SIN ( GAMAZS))               288
      HYPOTS = SQRT  (XWAVES**2+(VRUNO2-YWAVFS)**2 +(HKELEV-ZWAVES)**2) 289
      RESULS = SQRT  (( DHAS - XWAVES)**2 + YWAVES**2 + ZWAVES**2)      290
      DLENS  = HYPOTS + RESULS                                          291
      DELS   = HYPOTS + RESULS + SPLITS - TLENS2 - PLENS                292
      IF(DELS .LT. 0 ) 116,117                                          293
  116 DELS   = 0.0                                                      294
  117 PELS   = PELS2                                                    295
      TELFS  = (DELS * PELS ) / TLENS2 * 100.0                          296
      IF (TELFS .LE. 0 ) 118,119                                        297
  118 DTENS = TELFS = PELS2 = 0.0                                       298
  119 DTENS = C1 * TELFS **3 + C2 * TELFS **2 + C3 * TELFS              299
      IF (DTENS.LT. 0)     DTENS = 0                                    300
```

```
      PELS2 = PEAS = DTENS                                              301
      RTINS = RINS + CE = ( TOLENS - TLENS2)*( CD + (ROWS2 / 12.0 )**2) 302
      RACS  = RACS2                                                     303
      RACS2 = ( DTENS + ROWS2 / 12.0 - BRAKEC + RSPS2** BRAKEX) /RTINS  304
      HOOKS = DTENS*COS  ( ATAN  ( XWAVES / SQRT  ((HKELEV-ZWAVES)       305
     1 **2 + (VRUNO2-YWAVES) **2 )))                                     306
      ALL STBD CALCULATIONS DONE / TEST NEXT FOR KINK WAVE LOCATION      307
      IF ( XWAVES .GE. DWAS ) 120,130                                   308
  120 GAMAXS = ATAN  ( SQRT  ( HKELEV**2 + VRUNO2**2)/XWAVES)           309
      GAMAYS = ATAN  ( XWAVES / VRUNO2 )                                310
      GAMA7S = ATAN  ( HKELEV / SQRT  ( VRUNO2**2 + XWAVES**2 ))        311
      XWAVES = 0.0                                                      312
      YWAVES = VRUNO2                                                   313
      ZWAVES = HKELEV                                                   314
      HYPOTS = 0.0                                                      315
      STATEMENT 130 BEGINS FINAL CALCULATIONS                          316
  130 VHOOK  = HOOKP + HOOKS                                           317
      VFRICT = .0002666 * VELNS2                                       318
      IF ( VFRICT .LE. .018 ) 131,132                                  319
  131 VFRICT = .018                                                    320
  132 VROLL  = VFRICT * VWEIGH                                         321
      VADRAG = ( VELNS2 + WINDFT)**2 * DRAGK                           322
      VTDRAG = VADRAG + VROLL                                          323
      VACCG  = VACC2 / 32.174                                          324
      VACC   = VACC2                                                   325
      VACC2  = ( VTHRUS - VHOOK - VTDRAG)/ VMASS                       326
      RPOP   = RPOP2                                                   327
      RPOS   = RPOS2                                                   328
      ROWP   = ROWP2                                                   329
      ROWS   = ROWS2                                                   330
      TLENP  = TLENP2                                                  331
      TLENS  = TLENS2                                                  332
      VELNST = VELNS2                                                  333
      VRUNOT = VRUNO2                                                  334
      RSPP   = RSPP2                                                   335
      RSPS   = RSPS2                                                   336
      RSPPR  = RSPP * 9.5493                                           337
      RSPSR  = RSPS * 9.5493                                           338
      RACPR  = RACP * 572.9578                                         339
      RACSR  = RACS * 572.9578                                         340
      SAVE MAXIMUM VALUES BEGINS AT STATEMENT 200 , ENDS AT 215        341
  200 IF ( AVHOOK .LT. VHOOK) 201,202                                  342
  201 AVHOOK = VHOOK              S ATHOOK  = TIME                      343
  202 IF ( ADTENP .LT. DTENP) 203,204                                  344
  203 ADTENP = DTENP              S ATDENP  = TIME                      345
  204 IF ( ADTENS .LT. DTENS) 205,206                                  346
  205 ADTENS = DTENS             S ATDENS  = TIME                       347
  206 IF ( AVACCG .GT. VACCG) 207,208                                  348
  207 AVACCG = VACCG             S ATVACG  = TIME                       349
  208 IF ( ARSPP  .LT. RSPPR) 209,210                                  350
```

```
  209 ARSPP    = RSPPR                      $ ATRSPP  = TIME                351
  210 IF ( ARSPS  .LE. RSPSR) 211,212                                       352
  211 ARSPS   = RSPSR                       $ ATRSPS  = TIME                353
  212 IF ( ARACP  .LT. RACPR) 213,214                                       354
  213 ARACP   = RACPR                       $ ATRACP  = TIME                355
  214 IF ( ARACS  .LT. RACSR) 215,216                                       356
  215 ARACS   = RACSR                       $ ATRACS  = TIME                357
C     MAIN LOOP OUTPUT AND TAPE STORE LOGIC BEGINS HERE                     358
  216 CONTINUE                                                              359
      IF(TIME.EQ.0)GO TO 300                                               360
      IGL = IGL + 1                                                        361
      IF(IGL.EQ.10)402,400                                                 362
  402 IGL = 0                                                              363
  300 DATUM(1)=VELNSTSDATUM(9) =TIME SDATUM(17)=TELFPSDATUM(25)=DLENS       364
      DATUM(2)=VRUNOTSDATUM(10)=RSPPRSDATUM(18)=RLTP SDATUM(26)=PELS2       365
      DATUM(3)=VHOOK SDATUM(11)=RPOP SDATUM(19)=RTINPSDATUM(27)=DELS        366
      DATUM(4)=VROLL SDATUM(12)=ROWP SDATUM(20)=RACPRSDATUM(28)=TELFS       367
      DATUM(5)=VTDRAGSDATUM(13)=TLENPSDATUM(21)=RSPSRSDATUM(29)=RLTS        368
      DATUM(6)=DTENP SDATUM(14)=DLENPSDATUM(22)=RPOS SDATUM(30)=RTINS       369
      DATUM(7)=DTENS SDATUM(15)=PELP2SDATUM(23)=ROWS SDATUM(31)=RACSR       370
      DATUM(8)=VACCG SDATUM(16)=DELP SDATUM(24)=TLENSSDATUM(32)=0.0         371
      WRITE (7) DATUM                                                      372
  400 IF(TIME.LE.3.0)301,304                                               373
  301 IF(LTCONT-10*JTIME)304,302,302                                       374
  302 PRINT 90 , XWAVEP, YWAVEP, ZWAVEP, VKINKP, TIME, XWAVES, YWAVES,     375
    1 ZWAVES, VKINKS, TIME                                                 376
  303 JTIME = JTIME + 1                                                    377
  304 GO TO 99                                                             378
C     MAIN COMPUTATION LOOP DONE FINAL OUTPUT BEGINS WITH STATEMENT 1000   379
 1000 REWIND 7                                                             380
C     PRINT OUT MAXIMUM VALUES OF PARAMETERS AND TIME OF OCCURANCE         381
      PRINT 1001                                                          382
 1001 FORMAT (43X,7HMAXIMUM, 24X, 4HTIME )                                383
      PRINT 1002, AVHOOK, ATHOOK                                          384
 1002 FORMAT (10H HOOKLOAD, 28X, F12.4, 3H LB, 13X, F10.4, 4H SEC)        385
      PRINT 1003, ADTENP, ATDENP                                          386
 1003 FORMAT (19H   TAPE TENSION-PORT,19X,F12.4,3H LB,13X,F10.4,4H SEC)   387
      PRINT 1004, ADTENS, ATDENS                                          388
 1004 FORMAT (19H   TAPE TENSION-STBD,19X,F12.4,3H LB,13X,F10.4,4H SEC)   389
      PRINT 1005, AVACCG, ATVACG                                          390
 1005 FORMAT (22H   VEHICLE DECELERATION, 16X, F12.4, 4H G S, 12X, F10.4, 391
    1 4H SEC)                                                             392
      PRINT 1006, ARSPP, ATRSPP                                           393
 1006 FORMAT (17H   REEL SPEED-PORT,21X,F12.4,4H RPM,12X,F10.4, 4H SEC)   394
      PRINT 1007, ARSPS, ATRSPS                                           395
 1007 FORMAT (17H   REEL SPEED-STBD,21X,F12.4,4H RPM,12X,F10.4, 4H SEC)   396
      PRINT 1008, ARACP, ATRACP                                           397
 1008 FORMAT (24H   REEL ACCELERATION-PORT, 14X, F12.4, 7H RPM SQ, 9X,    398
    1 F10.4, 4H SEC)                                                      399
      PRINT 1009, ARACS, ATRACS                                          400
```

```
1009 FORMAT (24H   REEL ACCELERATION-STBD, 14X, F12.4, 7H RPM SQ, 9X,    401
    1 F10.4, 4H SEC)                                                     402
1010 JTIME = 1                                                           403
1050 JCOUNT = 0                                                          404
     PRINT 1052                                                          405
1052 FORMAT (9H1 VEHICLE)                                                406
     PRINT 1054                                                          407
1054 FORMAT (106H0   VELOCITY      RUNOUT      HOOKLOAD    ROLL FRICT  TOT 408
    1AL DRAG  TENSION/P   TENSION/S  ACCELERATION   TIME)               409
     PRINT 1056                                                          410
1056 FORMAT (106H      FT/SEC         FT          LB            LB       411
    1 LB        LB          LB            G          SEC,/)              412
1058 READ (7) DATUM                                                      413
1060 LTCONT = DATUM(9)*1000.0                                            414
     IF(LTCONT-10*JTIME)1058,1064,1064                                  415
1064 PRINT 1066, ( DATUM (I) , I = 1,9 )                                 416
     IF(DATUM(9).GE.2.0)1063,1065                                       417
1063 JTIME = JTIME + 10                                                  418
     GO TO 1068                                                          419
1065 JTIME = JTIME + 1                                                   420
1066 FORMAT (7F12.2,F12.4,F12.8)                                         421
1068 TIM = TIME-.01                                                      422
     IF(DATUM(9).GE.TIM)1072,1070                                       423
1070 JCOUNT = JCOUNT + 1                                                 424
     IF ( JCOUNT .GE. 50 ) 1050,1058                                    425
1072 REWIND 7                                                            426
1073 JTIME = 1                                                           427
1074 JCOUNT = 0                                                          428
     PRINT 1076                                                          429
1076 FORMAT (11H1 PORT SIDE)                                             430
     PRINT 1078                                                          431
1078 FORMAT (108H    REEL      REEL     RADIUS  TAPE    HOOK PT    PEND  432
    1 TOTAL   ELONG      TAPE     TAPE ON   TOTAL        REEL)          433
     PRINT 1080                                                          434
1080 FORMAT (116H   SPEED    POSITION    WRAP   ON DECK TO SHEAVE  ELONG 435
    1 ELONG  FACTOR    TENSION    REEL     INERTIA      ACC      TIME)  436
     PRINT 1082                                                          437
1082 FORMAT (116H    RPM       RAD         IN      FT       FT       FT  438
    1  FT      X        LB        FT    SLUG-FT SQ   RPM SQ     SEC)     439
1084 READ (7) DATUM                                                      440
1086 LTCONT = DATUM(9)*1000.0                                            441
     IF(LTCONT - 10*JTIME)1084,1090,1090                               442
1090 PRINT 1092, ( DATUM(I), I=10,17 ), DATUM(6), DATUM(18),           443
    1 DATUM(19), DATUM(20), DATUM(9)                                    444
     IF(DATUM(9).GE.2.0)1087,1091                                      445
1087 JTIME = JTIME + 10                                                  446
     GO TO 1094                                                          447
1091 JTIME = JTIME + 1                                                   448
1092 FORMAT (F9.3,F10.3,F9.3,F8.2,F9.3,2(F8.3),F8.4,F10.1,F8.2,F12.3,   449
    1F11.3,F8.3)                                                        450
```

```
1094 TIM = TIME-.01                              451
     IF(DATUM(9).GE.TIM)1098,1096               452
1096 JCOUNT = JCOUNT + 1                         453
     IF ( JCOUNT .GE. 50 ) 1074,1084            454
1098 REWIND 7                                    455
     JGEOR = JGEOR + 1                           456
2000 STOP                                        457
     END                                         458
```

APPENDIX B - VARIABLE NAMES, TYPES, DEFINITIONS, AND UNITS (NAMES ENDING WITH THE LETTER "P" REPRESENT PORT SIDE VALUES; THOSE ENDING IN "S" REPRESENT THE CORRESPONDING STARBOARD VALUES)

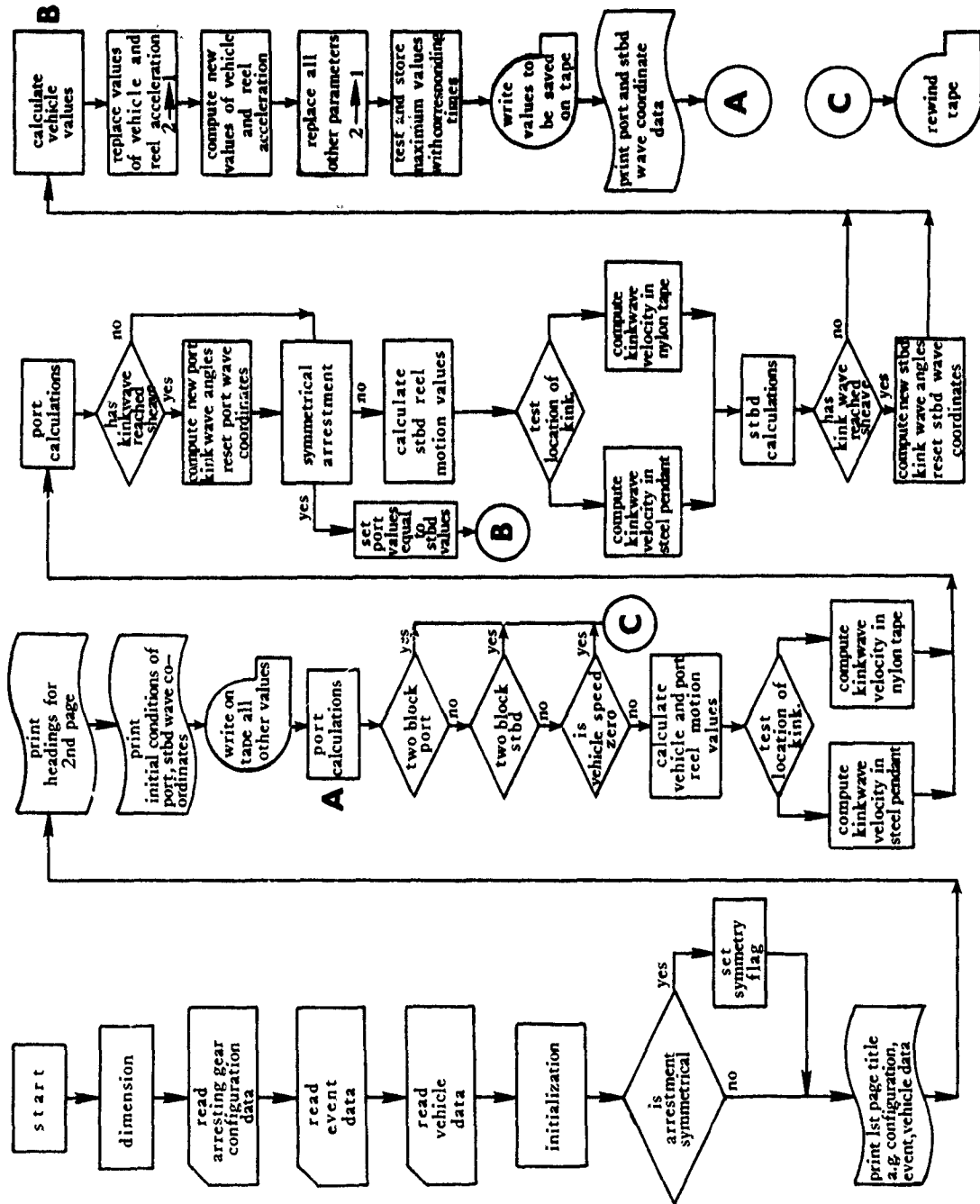| Variable Name | Input | Output | Intermediate | Definition | Units |
|---|---|---|---|---|---|
| ADTENP(S) | | X | | Maximum tape tension | Lb |
| ARACP(S) | | X | | Maximum reel angular acceleration | Rad/Sec$^2$ |
| ARSPP(S) | | X | | Maximum reel angular velocity | Rad/Sec |
| ATDENP(S) | | X | | Time at which AVHOOK occurs | Sec |
| ATHOOK | | X | | Time at which ADTENP(S) occurs | Sec |
| ATRACP(S) | | X | | Time at which ARACP(S) occurs | Sec |
| ATRSPP(S) | | X | | Time at which ARSPP(S) occurs | Sec |
| ATVACG | | X | | Time at which AVACCG occurs | Sec |
| AVACCG | | X | | Maximum vehicle acceleration | G |
| AVHOOK | | X | | Maximum vehicle arresting-hook axial load | Lb |
| BARO | X | | | Barometric pressure | In. Hg |
| BRAKEC | X | | | Tape reel brake constant | None |
| BRAKEX | X | | | Water brake exponent | None |
| C1 | X | | | Coefficient for tape tension equation | None |
| C2 | X | | | Coefficient for tape tension equation | None |
| C3 | X | | | Coefficient for tape tension equation | None |
| CA | | | X | $\dfrac{\text{Tape thickness}}{2\pi}$ | In. |
| CD | | | X | $\left(\dfrac{\text{Hub radius}}{12}\right)^2$ | Ft$^2$ |
| CE | | | X | $\dfrac{\text{Tape weight per foot}}{2g}$ | $\dfrac{\text{Lb-Sec}^2}{\text{Ft}}$ |
| CPEND | | | X | Stress propagation velocity-pendant | Ft/Sec |
| CTAPEP(S) | | | X | Stress propagation velocity-tape | Ft/Sec |
| DATUM(32) | | | X | Linear array dimension | None |
| DELP(S) | | | X | Total elongation (tape and pendant) | Ft |
| DELTIM | X | | | Incremental time for each calculation | Sec |
| DHAP(S) | | | X | Distance - sheave to point of engagement | Ft |
| DKSPAN | X | | | Distance between runway-edge sheaves | Ft |
| DLENP(S) | | | X | 3D distance, hook-point-to-kink-to-sheave | Ft |
| DOFFC | X | | | OFF-CENTER engaging distance (starboard +) | Ft |
| DRAGK | | | X | Drag factor | $\dfrac{\text{Lb-Sec}^2}{\text{Ft}^2}$ |
| DTENP(S) | | | X | Tension in tape and pendant | Lb |

| Variable Name | Type: Input | Type: Output | Type: Intermediate | Definition | Units |
|---|---|---|---|---|---|
| ETAPEP(S) | | | X | Tape modulus of elasticity | $Lb/Ft^2$ |
| GAMAXP(S) | | | X | Angle, initial pendant position-to-sheave-to-kink | Deg |
| GAMAYP(S) | | | X | Angle, intersection of line of engagement and projection of line from sheave to kink | Deg |
| GAMAZP(S) | | | X | Angle, kink-to-sheave-to-projection of kink on deck | Deg |
| HKELEV | | | X | Hook point elevation at any instant | Ft |
| HOOKHI | X | | | Elevation of hook attach point on vehicle | Ft |
| HOOKP(S) | | | X | Component of arresting-hook axial load | Lb |
| HYPOTP(S) | | | X | 3D distance, hook point to kink | Ft |
| ICOUNT | | | X | Output printer line counter | None |
| IFLGSM | | | X | Engagement symmetry flag | None |
| IGL | | | X | Output generation increment counter | None |
| JCOUNT | | | X | Line counter | None |
| JGEOR | | | X | Program sequential run indicator | None |
| LTCONT | | | X | Calculation increment counter | None |
| PEAP(S) | | | X | Used to segment pendant elongation equation | $\frac{1}{Lb\text{-}Ft^3}$ |
| PELP(S) | | | X | Pendant elongation | Ft |
| PENDEN | X | | | Pendant density | $\frac{Lb\text{-}Sec^2}{Ft^4}$ |
| PENLEN | X | | | Total unelongated pendant length (eye-to-eye) | Ft |
| PENMOD | X | | | Modulus of elasticity of the pendant | $Lb/Ft^2$ |
| PENSIG | | | X | Transverse impact equation approximation for pendant | None |
| PENX | X | | | Pendant cross-sectional area | $In.^2$ |
| PLENP(S) | | | X | Pendant length (unelongated) | Ft |
| POFFC | X | | | Pendant off-center distance (starboard +) | Ft |
| RACP(S) | | | X | Reel angular acceleration | $Rad/Sec^2$ |
| RACP(S)R | | | X | Reel angular acceleration | $Rev/Min^2$ |
| RESULP(S) | | | X | 3D distance, kink to sheave | Ft |
| RHUB | X | | | Tape reel hub radius | In. |
| RINP(S) | X | | | Tape-reel inertia (metal) | $Slug\text{-}Ft^2$ |
| RLTP(S) | | | X | Length of tape on reel (not on deck) | Ft |
| RNWIP(S) | | | X | Initial number of tape wraps on reel | None |

| Variable Name | Type In-put | Type Out-put | Type Inter-me-diate | Definition | Units |
|---|---|---|---|---|---|
| ROWP(S) | | | X | Tape outer wrap radius | In. |
| RPOP(S) | | | X | Reel angular position (beginning of time increment) | Rad |
| RPOP2(S2) | | | X | Reel position (end of time increment) | Rad |
| RSPP(S) | | | X | Reel angular velocity | Rad/Sec |
| RSPP(S)R | | | X | Reel angular velocity | Rev/Min |
| RTINP(S) | | | X | Total reel inertia | Slug-Ft$^2$ |
| SPLITP(S) | X | | | Split distance (from runway sheave to tape reel) | Ft |
| TAPDEN | | | X | Tape density | $\frac{\text{Lb-Sec}^2}{\text{Ft}^4}$ |
| TAREA | | | X | Tape cross-sectional area | In.$^2$ |
| TASIGP(S) | | | X | Transverse impact equation approximation for tape | None |
| TELFP(S) | | | X | Tape elongation factor | % |
| TEMPA | X | | | Temperature (ambient) | °F |
| THDEL | | | X | $\frac{\text{DELTIM}}{2}$ | Sec |
| THETAP(S) | | | X | Kink angle | Deg |
| TIME | | | X | Absolute accumulative time | Sec |
| TINP(S) | | | X | Initial length connector to sheave | Ft |
| TLENOP(S) | X | | | Initial tape on deck | Ft |
| TLENP(S) | | | X | Tape on deck at beginning of time increment | Ft |
| TLENP2(S2) | | | X | Tape on deck at end of time increment | Ft |
| TOLENP(S) | | | X | Total purchase-tape length | Ft |
| TTHICK | X | | | Purchase-tape thickness | In. |
| TWGHT | X | | | Purchase-tape unit weight | Lb/Ft |
| TWIDE | X | | | Purchase-tape width | In. |
| VACC | | | X | Vehicle acceleration at the beginning of the time increment | Ft/Sec$^2$ |
| VACC2 | | | X | Vehicle acceleration at the end of the time increment | Ft/Sec |
| VACCG | | | X | $\frac{\text{Vehicle acceleration}}{32.17}$ | G |
| VADRAG | | | X | Vehicle aerodynamic drag | Lb |
| VCOAD | X | | | Vehicle coefficient of aerodynamic drag | None |
| VELENG | X | | | Vehicle engaging speed | Kn |
| VELNST | | | X | Vehicle speed at beginning of time increment | Ft/Sec |
| VELNS2 | | | X | Vehicle speed at end of time increment | Ft/Sec |
| VFRICT | X | | | Coefficient of rolling resistance | None |
| VHKLEN | X | | | Vehicle arresting-hook length | Ft |
| VHOOK | | | X | Vehicle arresting-hook axial load | Lb |

| Variable Name | Type | | | Definition | Units |
|---|---|---|---|---|---|
| | In-put | Out-put | Inter-me-diate | | |
| VKINKP(S) | | | X | Kink-wave velocity | Ft/Sec |
| VMASS | | | X | Vehicle mass | $\frac{Lb\text{-}Sec^2}{Ft}$ |
| VROLL | | | X | Vehicle rolling resistance load | Lb |
| VRUNOT | | | X | Vehicle runout at beginning of time increment | Ft |
| VRUNO2 | | | X | Vehicle runout at the end of time increment | Ft |
| VTDRAG | | | X | Vehicle total drag | Lb |
| VTHRUS | X | | | Vehicle thrust | Lb |
| VWEIGH | X | | | Vehicle weight | Lb |
| WINDFT | | | X | Head-wind velocity | Ft/Sec |
| WINDKT | X | | | Head-wind velocity | Kn |
| XWAVEP(S) | | | X | Kink X-distance from point of engagement | Ft |
| YWAVEP(S) | | | X | Kink Y-distance from point of engagement | Ft |
| ZWAVEP(S) | | | X | Kink Z-distance from point of engagement | Ft |

APPENDIX C -- GENERAL FLOW CHART

B

calculate vehicle values → replace values of vehicle and reel acceleration 2→1 → compute new values of vehicle and reel acceleration → replace all other parameters 2→1 → test and store maximum values with corresponding times → write values to be saved on tape → print port and stbd wave coordinate data → A    C → rewind tape

port calculations → has kinkwave reached sheave → no / yes → compute new port kink wave angles reset port wave coordinates → symmetrical arrestment → no → calculate stbd reel motion values → test location of kink → compute kinkwave velocity in nylon tape / compute kinkwave velocity in steel pendant → stbd calculations → has kink wave reached sheave → no / yes → compute new stbd kink wave angles reset stbd wave coordinates

yes → set port values equal to stbd values → B

print headings for 2nd page → print initial conditions of port, stbd wave co-ordinates → write on tape all other values → A port calculations → two block port → yes / no → two block stbd → yes / no → is vehicle speed zero → yes / no → C → calculate vehicle and port reel motion values → test location of kink → compute kinkwave velocity in nylon tape / compute kinkwave velocity in steel pendant

start → dimension → read arresting gear configuration data → read event data → read vehicle data → initialization → is arrestment symmetrical → yes → set symmetry flag / no → print 1st page title a.g. configuration, event, vehicle data

C-1

APPENDIX D - DETERMINATION OF KINK-WAVE VELOCITY

1. The location of the kink wave with time is an important factor in the mathematical model design. The kink wave's position on the runway determines the overall pendant/tape geometry which governs the operation of the program. The change in runway geometry directly affects the two most important arrestment parameters: tape tension and arresting-hook load.

2. The location of the kink wave is determined by its velocity alone because its path is predetermined by model design. In this model, the kink wave, upon hook impact with the pendant, follows a straight line path from the position of hook impact to the runway-edge sheave (kink one). Upon impact on the sheave, it then follows a new path which is a straight line from the position of the hook at sheave impact to the runway-edge sheave (kink two). The establishment of kink-wave paths is illustrated below:



SHEAVE
IMPACT

KINK ONE                                    KINK TWO
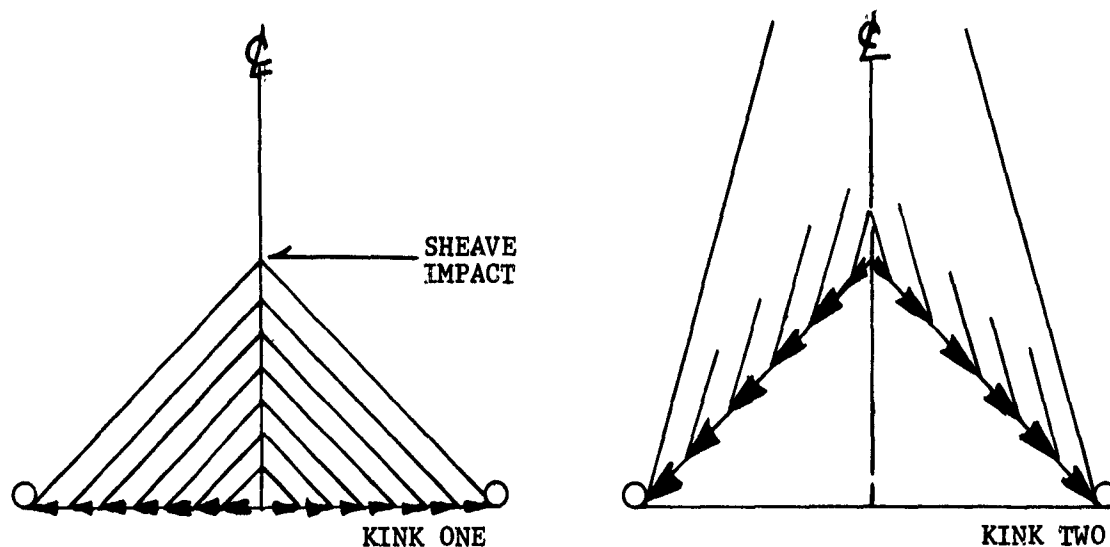
3. The approach to the problem of determining kink-wave velocity is based on information presented in "Cable Dynamics" by F. O. Ringleb (reference (a) of basic text), and the method of solution presented here follows from his work.

4. It is assumed that the arresting hook of the aircraft engages the pendant perpendicularly and results in transverse impact. A triangle-shaped deformation is formed in the pendant due to impact. A stress wave propagates along the pendant toward the sheaves with a finite

velocity ahead of and faster than the deformation. The velocity at which the kink wave propagates along the pendant while this is happening is established below:

NOTE:  Ringleb's analysis applies only to an infinitely long cable. The assumptions made in the model design are:  1, The calculation of the kink-wave velocity in the purchase-tape media follows the same principles that pendant calculations are based on and 2, the equations of motion described are used even after kink one reflects off of the runway-edge sheave and the pendant/tape configuration no longer appears to be like an infinitely long cable.

Letting:

E = modulus of elasticity of pendant (tape)

$\rho$ = mass density of pendant (tape)

$\sigma$ = stress

$\sigma_0$ = initial stress

Then from the classical theory of a vibrating string, the longitudinal wave velocity C is:

$$C = \sqrt{\frac{E}{\rho}}$$

and the transverse wave velocity $\overline{C}$ is

$$\overline{C} = \sqrt{\frac{\sigma}{\rho}} .$$

C is the velocity of stress propagation in the medium of concern, and $\overline{C}$ is the velocity that the deformation propagates with respect to a particular defined mass point in the media (pendant) at time of impact (t = 0). The following diagram shows a segment of the pendant impact:
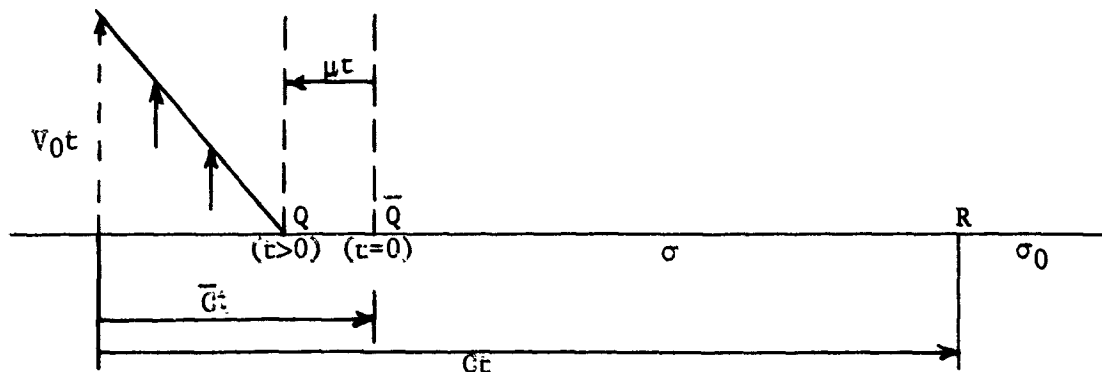
In the preceding diagram, the motion of a point mass $\bar{Q}$ of the pendant at time 0 is analyzed to define kink-wave motion. After impact, $t > 0$, this point mass is designated Q and marks the location of the kink wave on its way toward the sheave. R represents the point that the stress has reached at $t > 0$. The point $\bar{Q}$ moves toward the right with the transverse wave velocity $\bar{C}$ while the pendant segment QR moves toward the left with a velocity $\mu$ (from the longitudinal impact formula $\sigma - \sigma_0/E = \mu/C$). Thus the velocity of the kink wave, W, is given by the relationship $W = \bar{C} - \mu$. Now, $\bar{C}$ can be expressed in terms of E and $\sigma$ since

$$C = \sqrt{\frac{E}{\rho}} \text{ it follows that } \frac{1}{\sqrt{\rho}} = \frac{C}{\sqrt{E}}$$

so that substituting $\frac{C}{\sqrt{E}}$ for $\frac{1}{\sqrt{\rho}}$ into the formula for $\bar{C}$ gives

$$\bar{C} = \sqrt{\frac{\sigma}{\rho}} = \sqrt{\frac{1}{\rho}} \times \sqrt{\sigma} = \frac{1}{\sqrt{\rho}} \times \sqrt{\sigma} = \frac{C}{\sqrt{E}} \times \sqrt{\sigma} = C\sqrt{\frac{\sigma}{E}} \,,$$

the kink-wave velocity can therefore be expressed as

$$W = C \left( \sqrt{\frac{\sigma}{E}} - \frac{\sigma - \sigma_0}{E} \right).$$

5. An expression for the term $\frac{\sigma - \sigma_0}{E}$, which represents an approximation of the transverse impact formula (reference (a) of main text), is given as,

$$\frac{\sigma - \sigma_0}{E} = \left( \frac{1}{2} \right)^{2/3} \left( \frac{V_0}{C} \right)^{4/3} \,,$$

where $V_0$ is the impact velocity. So that finally, the kink-wave velocity for an infinitely long cable is:

$$W = C \left( \sqrt{\frac{\sigma}{E}} - \left( \frac{1}{2} \right)^{2/3} \left( \frac{V_0}{C} \right)^{4/3} \right).$$

NOTE: The kink-wave velocity in this model is computed with this equation modified with an additive factor accounting for the tape "feed in" velocity as the tape reel responds to the acceleration forces during an actual arrestment.

## APPENDIX E - DETERMINATION OF THE MODULUS OF ELASTICITY

1. The value of modulus of elasticity for both steel (pendant) and nylon (tape) is required in the program to account for kink-wave motion. The value for the pendant is a constant value and is input into the program. The value for nylon tape varies with tape stretch and an expression must be derived to represent it. Therefore, a mention of elasticity theory and the method of derivation of an appropriate modulus equation for nylon tape follows.

2. The modulus of elasticity is a measure of the effect that tension has on a material. Many materials exhibit a stretching (deformation) in direct proportion to the amount of tension applied (loading). This relationship is given by Hooke's law:

$$E = \frac{S}{\epsilon} .$$

where     $E$ = modulus of elasticity   lb/in.$^2$,

           $S$ = stress   lb/in.$^2$,

and       $\epsilon$ = strain   in./in.

If        $L$ = original length of material,

           $A$ = original area of material,

           $P$ = applied tension load,

and       $\delta$ = elongation of material,

then                 $S = P/A$ and $\epsilon = \delta/1$

so that                $E = \frac{PL}{A\delta}$ .

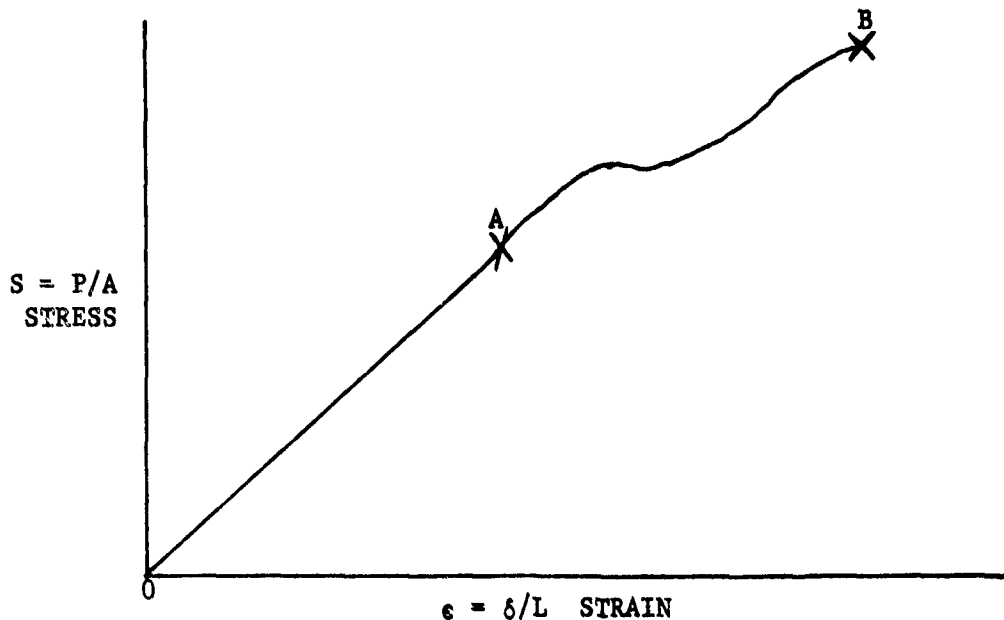Plotting P/A against δ/L, we obtain the typical stress-strain curve:



Figure E1

Line OA is linear and represents the elastic range of a material. In this range, no permanent deformations are produced by stresses. Hooke's law applies only in this region. Curve AB represents the plastic range of a material. Here, permanent deformations or sets occur upon applied loading. Point B shows where the test material fails. The slope of the line OA is the modulus of elasticity of the material. Stresses and strains along this line follow the "linear theory of elasticity".

3. Modulus of Elasticity of Steel Pendant: The stress-strain diagram for a steel pendant closely resembles that of Figure E1. The value of modulus used in the program is taken from data for steel wire cables with hemp core containing 6 strands with 19 wires each. The value is $E = 13,000,000$ lb/in.$^2$ (page 13 of reference (a) of basic text). This value varies considerably from that of steel--$E = 30,000,000$ lb/in.$^2$-- indicating that a pendant of this type is less stiff than a corresponding solid element.

4. <u>Modulus of Elasticity of Nylon Tape</u>: Due to the inhomogeneity of the nylon threads and the fabric nature of nylon tapes, the stress-strain diagram representing the tensile test of a piece of nylon tape differs considerably from that of Figure E1:
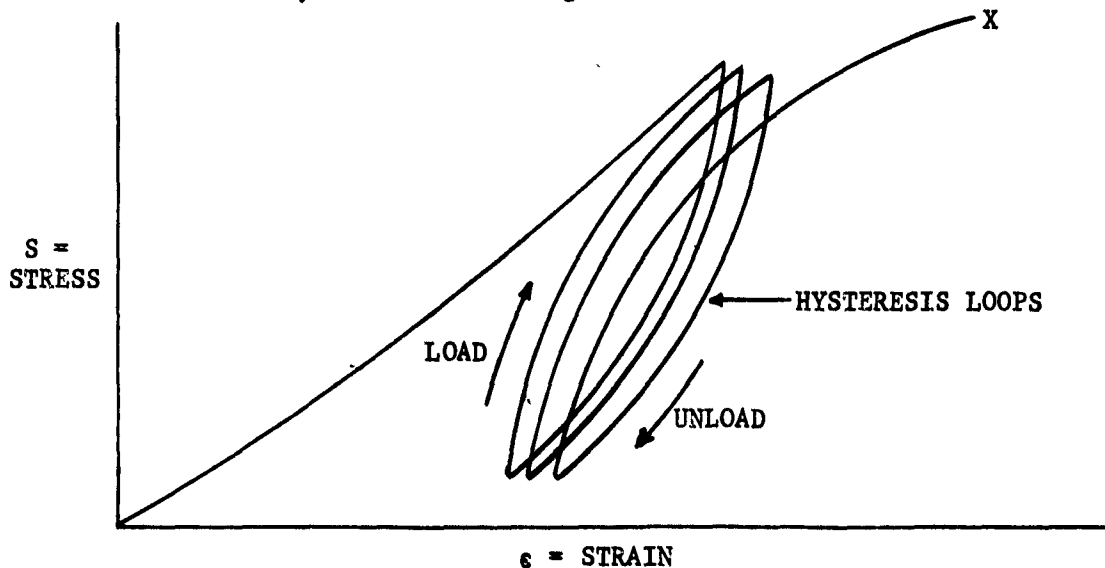


Figure E2

Nylon tape used on the arresting gears are actually plastic in nature. When a load is applied to a specimen in stepped increments and then unloaded, the curve representing this action does not return to where it originated but shows evidence of permanent tape elongation. Upon repeated loadings and unloadings, loops are formed representing the tape's inelasticity. After the initial pull, the loops that are generated originate in approximately the same area. Also, the plastic deformations are somewhat predictable and therefore can be thought of as uniform plastic deformations. For these reasons, a value for modulus of elasticity of nylon tape can be obtained by considering the uniform plastic deformation to be elastic in nature and thereby obtain an approximate value for the modulus by applying elastic theory methods (modulus is slope of stress-strain curve) to the curves.

5. <u>Procedure</u>

    a. Obtain pull-test data for particular nylon tape from the NAVAIRTESTFAC Engineering Department Recovery Division (load 1b - stretch in.).

    b. Convert data to a stress-percent tape elongation curve.

    c. Curve fit best 3rd-degree curve through data to obtain equation that represents stress as a function of strain.

      d.  Differentiate equation to obtain a new equation that represents the slope of the stress-strain curve and is the modulus of the tape as a function of tape elongation.

## APPENDIX F - DETERMINATION OF TAPE-REEL ACCELERATION

1. Tape-reel acceleration is one of the key "motion producing" parameters of the program (see Simulated Arrestment Description, Section V of main text). The importance of this parameter necessitates an explanation of the equations that represent it.

2. _Tape-Reel Acceleration:_ The equation for angular acceleration of the tape reel is obtained from the relationship:

$$\Sigma T = I\alpha,$$

where   $\Sigma T$ = sum of the torques acting on the reel and rotor,

   $I$ = polar moment of inertia of the rotating reel,

and   $\alpha$ = angular acceleration of the reel and rotor.

   a. The $\Sigma T$ term is the sum of the torque created by the tape tension force applied at the radius of the outer wrap of the tape ($T_{tt}$) and the retarding torque developed in the water brake ($T_{wb}$),

or   $$\Sigma T = T_{tt} + T_{wb}$$

   (1) $T_{tt} = T_t R_t$

where   $T_t$ = purchase-tape tension

and   $R_t$ = radius of outer tape wrap on the reel.

   (2) $T_{wb} = B \cdot w^n$

where   $B$ = hydrodynamic brake constant,

   $w$ = angular velocity of reel and rotor,

and   $n$ = brake exponent (constant).

The two constants, $B$ and $n$, are obtained from actual test data of a particular type gear. When the value of angular velocity $w$ reaches its maximum value for a test event, then the angular acceleration is minimized. Assuming that it becomes zero, $\alpha = 0$ and $w = w_m$ (maximum angular acceleration), from the original equation,

$$\Sigma T = I\alpha = 0$$

so that   $$\Sigma T = T_t R_t + B w_m^n = 0,$$

or   $$T_t R_t = B w_m^n .$$

The values of $T_t$ and $R_t$ are obtained from the test data at the time corresponding to the maximum angular velocity $W_m$. The values of B and n are then obtained by using the method of least squares.

   b. The I term is the sum of the tape-reel (metal) inertia $I_m$ and the instantaneous tape inertia $I_t$ $I = I_M + I_t$.

      (1) The value of tape-reel inertia $I_M$ is a constant value and is equal to 114 slug - ft for the E-28 arresting gear.

      (2) The value of the tape inertia $I_t$ varies as the tape is pulled off of the reel and is obtained by the expression

$$I_t = \tfrac{1}{2}M\ (R_H{}^2 + R_t{}^2)$$

where    M = instantaneous tape weight / g,

      $R_H$ = reel hub radius,

and    $R_t$ = instantaneous radius of outer tape wrap.

   c. Upon rearrangement of the described terms in the original equation, the expression for tape-reel acceleration, $\alpha$, is:

$$\alpha = \frac{\Sigma T}{I} = \frac{T_{tt} + T_{wb}}{I_M + I_t} = \frac{T_t\ R_t + Bw^n}{I_M + \tfrac{1}{2}M\ (R_H{}^2 + R_t{}^2)}\ .$$

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13. ABSTRACT

This mathematical model is designed to provide predicted dynamic performance
data of shorebased rotary-hydraulic-type aircraft arresting gears. A Navy Model
E-28 arresting gear is used for specific comparison between predicted results of
the computer solution and actual test results. The simulation of an arrestment
of a vehicle under a particular set of conditions is accomplished by putting in-
formation (data) into the computer. The input data specifies values for the in-
stallation geometry and mechanical properties of the arresting system and the
test vehicle. Predicted dynamic values of forces and motions of the test vehicle,
purchase system, and tape reel are printed out versus time at a predetermined
incremental time.

This report is a phase report on the development of the model and contains
the early analytical design approaches, the most current analytical approach
with the computer program, and instructions for execution of the computer
program.

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| MATHEMATICAL PERFORMANCE PREDICTION MODEL | | | | | | |

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